EXPERIMENTAL STUDIES ON VIBROVISCOSITY OF SOILS

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

BY

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to the

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

OCTOBER 1972

CERTIFICATE

Certified that this work "Experimental Studies on Vibroviscosity of Soils", has been carried out by Sri V.M. Bhagwat under my supervision and the same has not been submitted elsewhere for a degree.

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ACKNOWLEDGEMENTS

The present work was carried out under the able supervision of Dr. N.S.V.Kameswara Rao. The author is grateful to him for the constant help in the experiments, continuous encouragement and assistance throughout the manuscript. Suggestions received from Dr. S. Surya Rao and Dr. A.J. Valsangkar are gratefully acknowledged.

The author places on record his appreciation of the timely help received from Sri K.V. Lakshmidhar, Sri R.P. Trivedi and the staff of Soil Mechanics Laboratory.

Thanks to Sri R.K. Verma for the fabrication work of the necessary equipments.

Help received from Sri Guru Prasad and Sri M.S. Rahman is also appreciated.

To Sri G.S. Trivedi goes my thanks for his fine typing.

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NOTATIONS

The following are the notations used in the experiments:

S	=	Sinking of different bodies;
t	=	Time of sinking;
L	=	Length of the body;
D	=	Diameter of the body;
F	=	Surcharge weight;
d_p	=	Grain size of particles;
V	=	Velocity of Sinking;
S_1	=	Big sphere;
S_2	=	Small sphere;
S_3	=	Small cylinder with cone;
S_4	=	Big cylinder with cone;
θ	=	Angle of the cone;
μ	=	Coefficient of Vibroviscosity of soil;
ρ_{body}	=	Density of the body;
$\rho_{\cancel{part}\,b.}$	=	Density of the sand ~~particles~~ (Bulk)
γ_b	=	Unit weight of the body;
γ_s	=	Unit weight of the soil;
η	=	Acceleration of vibrations.

SYNOPSIS

Studies and observations of models footings and behaviour of foundations such as footings, piles etc. which are supported by soil medium, when subjected to shocks and vibrations show that they may undergo settlements many times larger than those imposed by static loads. It happens that settlement of foundations undergoing vibrations greatly endangers the safety of the structures. So it becomes important to study sinking behaviour of structures under vibrations.

The soil when subjected to intense vibrations tends to liquefy and behaves like a fluid. The coefficient of viscosity of fluidised soil medium is an important property which can be studied. The effect of soil parameters, vibration characteristics etc. on sinking behaviour of different shapes and vibroviscosity is also an important aspect for investigation.

In the experiments carried out here in, sinking pattern for different shapes when falling in vibroviscous medium was studied by changing various parameters. This knowledge is applied to get the vibroviscosity of the soil. The effect of soil parameters and vibration characteristics on vibroviscosity was also studied by conducting number of experiments.

In the present investigation Stokes Law for the terminal velocity of a sphere falling in stationary fluid of infinite extent is made use of for the evaluation of vibroviscosity. For shapes other than spheres, the equivalent sphere of same volume is made use of .

Laboratory tests were done on the sinking behaviour of four different bodies falling in vibroviscous medium. The vibroviscosity was found out by Stokes solution. The effect of grain size, density at the time of liquefaction, surcharge weights, operating frequency, acceleration of vibration etc. on sinking behaviour of bodies and vibroviscosity was studied. The graphs were plotted in dimensionless form.

CHAPTER I

INTRODUCTION

1.1 GENERAL:

The earthquakes which took place in the past clearly point out the fact that Nature is dynamic. Earthquakes are nothing but the vibrations or shocks given to the soil by natural causes. Vibrations due to nuclear blasts and other artificial means also are becoming quite common. The progress of industries is accompanied by increase in number of heavy machines in use, as well as by the introduction of blasting operations into construction practice and the increasing speed, intensity and tonnage of various kinds of transport. All these factors lead to an increase in influence of shocks and vibrations on natural soils.

The loose non-cohesive sands are very much vulnerable to the shocks and vibrations. It was seen that when a non-cohesive soil is subjected to dynamic loads, the resistance to external loads decreases considerably. This is verified by plunging vibrators, vibrating piles, pipes or cylinders into the soil. The loss of strength results due to changes in dissipative properties of soil e.g. forces of internal dry and viscous friction, forces of cohesion, forces of external friction, in the hydrodynamic properties

e.g. the coefficient of permeability and the pore water pressure and in elastic and plastic characteristics such as Young's modulus, the modulus of shear, and the limits of elasticity and plasticity etc.

1.2 VIBROFLOATATION AND VIBROVISCOSITY:

In addition, it was established that, if subjected to intense vibrations, sandy fills, loose silty and clayey soils get compacted at first and when the intensity of vibration is increased more and more, they lose their resistance to shear to such a degree that their mechanical properties are closer to those of viscous liquids than of solids. This phenomenon is called vibrofloatation. The stage at which the soil behaves as viscous fluid is called liquefaction. The coefficient of viscosity of the fluidised soil medium is called vibro-viscosity. This process results in the failure of structures founded on the soil.

1.3 IMPORTANCE OF THE STUDY OF LIQUEFACTION PHENOMENON:

The study of sand liquefaction has gained fresh impetus as a result of great damages that occured during several earthquakes at Niigata, Alaska, Tokachioki etc.

In India also the importance of such studies is being felt because of the increase in construction activities in the sesmically active zones.

The studies of liquefaction in European countries were limited to saturated sands only. Barkan[2] was the first who conducted his tests on dry sands and gave the concept of vibrofloatation.

The phenomenon of liquefaction has been studied by various investigators such as Seed[34], Florin and Ivanov[12], Yoshimi[43], Kishida[17], etc. They conclude that the factors which affect the liquefaction are:

(i) grain size
(ii) density of the sand deposit
(iii) surcharge weight
(iv) vibration characteristics
(v) location of drainage
(vi) dimensions of deposit etc.

Because the consequences of soil liquefaction are so severe the reliable prediction of occurance of this phenomenon is of vital importance.

1.4 OBJECT OF PRESENT STUDIES.

The object of the present investigation was to study two problems. (i) Falling of different bodies in vibroviscous medium (ii) Finding the vibroviscosity by Stokes Law and to see the effects of grain size, operating frequency, density of the deposit etc. on vibroviscosity.

Vibrofloatation studies in this thesis are limited to dry sands having fine to medium grain size. The sand is subjected to steady state vertical vibrations. The sinking behaviour of the objects in fluidized soil medium was studied with reference to shape and size of the body, superimposed loads, grain size of sand, operating frequencies, accelerations and amplitudes of vibrations. Dimensional analysis was carried out to present the results in dimensionless form.

CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION:

G.I. Pokrovasky[2] and associates were probably the first to investigate experimentally the influence of vibration on coefficient of internal friction. They show that coefficient of internal friction depends upon kinetic energy of vibrations; as the energy increases, the coefficient decreases approaching a value 25 to 30 percent smaller than that observed before vibrations.

In English countries and United States a qualitative understanding of sand liquefaction and its effects was first presented by Casagrande[9] in 1936. He explained the phenomenon of liquefaction through the "Critical Void Ratio" approach.

It was noted that during shear, dense sands tend to expand whereas loose sands tend to decrease in volume; thus for any sand there will be some initial void ratio termed as critical void ratio, for which no volume change during drained shear, (correspondingly, no pore water pressure changes during undrained shear), will occur. It was reasoned, therefore, that the sand deposits having a void ratio above the critical value and therefore tending to contract during shear, would, under undrained conditions develop positive

pore water pressures that would possibly become large enough to produce liquefaction. Conversely, deposits having an initial void ratio below the critical value would tend to dilate during shear, producing a decrease in pore water pressures and corresponding increase in effective stress, under undrained conditions, so that high strength and stability would develop.

Florin and Ivanov[12] describe the phenomenon of liquefaction as a mechanical break down of structure of sand, as well as by physical and chemical processes which occur in soils, and in particular by thixotropy.

Moslov[23] gave the theory of "Filtration" according to which every sand can be subjected to consolidation under sufficiently intense vibrations. The intensity of vibration depends upon the state of compaction of sand. The compression of sand leads to considerable increase in pore water pressure. The sand grains may be looked upon as if they have lost their weight. Thus, depending upon the initial density of sand, there is a "critical acceleration" value beyond which there will be an increase in pore water pressure and decrease in strength and further consolidation of soil.

2.2 PREVIOUS EXPERIMENTAL STUDIES:

Previous laboratory experiments to study the liquefaction phenomenon may be divided into two main groups. They are (i) A box containing saturated or dry sand subjected to vibrations or impact. (ii) A cylindrical specimen of saturated sand is subjected to cyclic variation in deviator stress while ambient pressure is kept constant.

All the tests from group one are conducted on sands either dry or saturated. The relationships between a few parameters of sand and operating frequency were established by Barkan[2].

The laboratory tests that belong to the second group have been conducted as undrained tests, and each cylindrical specimen has been supposed to represent an element within the soil mass. These samples are consolidated in a triaxial apparatus under appropriate stress conditions and alternating shear loads of controlled magnitude and frequencies are applied. Measurements of pore water pressure changes and of the deformation behaviour of samples are made so that the onset of liquefaction may be detected.

2.2.1 Test with Dry Soils:

Barkan[2] has carried out tests with dry sands and obtained a relationship between coefficient of vibroviscosity and acceleration of vibration. Sand was assumed to act like viscous fluid. He assumed that the relationship between the time of vibration and sinking of sphere to be linear. He used Stoke's Law for static fluids and found out the coefficient of vibroviscosity.

Dasgupta[11] carried out the tests on the motion of a sphere in soil medium subjected to vibrations. The vibroviscosity of the soil has been obtained using the analysis of the accelerated motion of sphere in an oscillating liquid and has been compared with the values obtained from Stokes classical solution.

2.2.2 Tests with Saturated Soils:

Barkan[2] conducted the tests on saturated soils also. He states that the magnitude of the forces of cohesion in soils depends on their moisture content which leads to the assumption that the coefficient of vibroviscosity also depends on moisture content.

Florin and Ivanov[12] made the study of liquefaction on saturated sandy soils. They carried out the vibration tests on 20 cm. thick sand deposit, both under steady

state and transient vibrations .

They report that the main feature of the sand transformation into liquefied state are decrease of porosity and temporary increase of pore water pressure. Under these conditions changes in porosity of sand have been measured. Their experiments lead to the following conclusions:

(i) If the sand is subjected to shock loading, the whole stratum gets liquefied at the same time, while under steady state vibrations the liquefaction starts from the top and proceeds downwards.

(ii) The grain size and superimposed loads affect the time for which the sand remains in liquefied state.

(iii) The upper layer of the soil remains liquefied much longer and in these layers, there is much greater displacement of liquefied soil or maximum sinking of heavy bodies.

(iv) The initial stress condition for saturated sandy soils, determined by the weight of the overburden or external applied load, reduces the possibility of sand liquefaction.

(v) They say that at a depth ranging from 10 to 15m. below ground level, even very loose sand can hardly be liquefied.

Hence surcharge with any material can be used as a method of reducing sand liquefaction.

(vi) The use of draining surcharge reduces not only the possibility of liquefaction but also if liquefaction has already occured, the period during which it will continue.

(vii) The presence of entrapped gas, the content of which may vary from 8 to 20 percent greatly influences the process of liquefaction.

Yoshimi[42] also made an investigation with loose saturated sand subjected to horizontal vibrations. He reports that:

(i) When sand undergoes complete liquefaction, the process leading to liquefied state consists of two stages: initial compaction and sudden liquefaction.

(ii) During the initial compaction process the pore water pressure at different depths increases uniformly and simultaneously while the sand remains stable. The duration of initial compaction increases with increasing surcharge and with decreasing acceleration.

(iii) Sudden and complete liquefaction occurs when effective stress in sand is reduced to a certain value as a result of initial compaction. The effective stress at the onset of sudden liquefaction occurs almost simulteneously at all depths.

Matsau and Ohara[24] reported results of tests on loose saturated sands performed on the vibration table. They found a sudden increase in pore water pressure occured at definite acceleration. The value confirmed the concept of critical acceleration given by Moslov[23].

2.3 TRIAXIAL TESTS:

Haung-Wen-Xi[15] obtained test data from triaxial tests performed by shaking the sample on vertically vibrating table. He used, density of the sand sample, acceleration of vibration and lateral pressure as variables in his study. He showed that the magnitude of pore water pressure depends not only on physical properties of sand but also on the vibration characteristics. The phenomenon of liquefaction, he concludes, occurs due to loss of contact between the grains by dynamic action, thereby causing gradual transfer of shear stress from grain to pore water.

Prakash and Mathur[30] studied the effect of frequency and amplitude of vibration on samples of same cross sectional area but different heights. Their results show:

(i) The pore water pressure attains a maximum value prior to resonance. At resonance the pore water pressure gets partially dissipated.

(ii) Excess hydrodynamic pressure induced is larger than that is required to cause liquefaction.

(iii) Liquefaction of the top layers occur first and subsequently the bottom one.

(iv) Settlement of deposit varies characteristically with acceleration of the table.

Seed and Lee[36] performed detailed tests in triaxial apparatus. They say that the magnitude of cyclic stress or strain, number of stress cycles to which the sand was subjected, void ratio of the sand and confining pressure of sand are the main points on which the phenomenon of liquefaction is dependant. The main observations are:

(i) Higher the void ratio more easily liquefaction will occur.

(ii) Lower the confining pressure liquefaction will take place easily.

(iii) Lower the stress or strain, fewer are the number of cycles to cause liquefaction.

Finn, Pickering, Bransby[13] conducted their tests in box shear appratus . They say that the field conditions are best approximated with cyclic loading shear tests carried out in a simple shear apparatus. They performed the set of triaxial tests and simple shear tests and then compared those results.

They report that important variable controlling the incidence of liquefaction in a given number of cycles, in a sand at a particular void ratio, is the initial effective stress ratio; the ratio of peak alternating stress to the initial effective mean normal stress. In physical terms, this is the ratio of stress that imparts to the sample a certain potential to resist the liquefaction. As long as the stresses are not so high that significant crushing of grains of sand will result, it appears that only the numerical value of this ratio is important and not the particular value of shear stress and the mean normal stress.

2.4 ANALYSIS OF VIBROFLOATATION:

2.4.1. Effect of Acceleration on Soil Behaviour:

Barkan[2] made the extensive studies of sand subjected to vibrations. He gave the emphirical relationship between coefficient of internal friction of sand and acceleration of vibration. It shows that as the acceleration increases the internal friction decreases and the decrease is rapid upto an acceleration ratio of 5.5 g Fig. (2.1) and the relation is expressed as:

$$\tan \phi = (\tan \phi_{st} - \tan \phi_{\infty}) \exp(-\beta\eta) + \tan \phi_{\infty} \quad (2.1)$$

where $\tan \phi_{st}$ = value of coefficient of internal friction without vibrations.

$\tan \phi_{\infty}$ = limit value of coefficient of internal friction.

η = ratio of acceleration of vibration to the acceleration of gravity

β = coefficient determining effect of vibrations (for dry medium grained sand, $\beta = 0.23$

It is imperative that at liquefaction the value of internal friction is zero theoretically but from above we can see that it is not zero in any case.

2.4.2 Effect of Moisture Content and Grain Size:

Barkan[2] showed that coefficient of internal friction decreases with the moisture content, the lowest value occuring at 13 percent of moisture content. Fig. (2.2).

The study of influence of grain size on effect of vibrations was performed on four varieties of sand under two regimes of vibrations. The values of coefficients of internal friction are different in the absence of vibrations; therefore, he says that it is advisible to compare, not the absolute values of the coefficients, but the values of δ characterizing the effect of vibrations thereon: where

$$\delta = \frac{\tan \phi_{st} - \tan \phi}{\tan \phi_{st}} \qquad \ldots\ldots \qquad (2.2)$$

where $\tan \phi_{st}$ and $\tan \phi$ are coefficients of internal friction respectively without and with vibrations. δ indicates the degree of decrease in the value of coefficient of internal friction Fig. (2.3).

2.4.3 Effect of Frequency and Amplitude on Soil:

Barkan[2] also established the relationship between the angular frequency of vibration verses internal friction tan ∅. The dependance of tan ∅ (∅ is the angle of internal friction of sand) for same angular frequency is more complicated. As frequency increases upto 180 radians per second, the coefficient slowly decreases; then, as the frequency increases still (from 180 to 250 radians per second) the coefficient of internal friction sharply decreases; and subsequent increase in the value of frequency has almost no effect on the coefficient of internal friction. The trend is shown in the Fig. (2.4).

He also gave the relationship between coefficient of internal friction tan ∅ and the amplitude of vibrations of a dry medium grained sand while the frequency remained constant. These graphs show that the coefficient of internal friction of sand decreases continuously as the amplitude increases. Fig. (2.5) and at very high amplitude it becomes asymptotic.

2.4.4 Effect of Acceleration on Vibroviscosity:

Barkan[2] was the first to study the phenomenon of vibrofloatation and thereby vibroviscosity of soils. He studied the effect of acceleration on vibroviscosity. He considered the behaviour of finely grained sand subjected

to vibratory loads to behave like a fluid and observed the sinking of sphere in vertically oscillating dry sand. He utilized Stokes law, which establishes the dependance of velocity 'v' of the motion of sphere in a static viscous fluid on the resistance acting thereon, the radius of sphere and the coefficient of viscosity of the fluid. He expressed the relationship for a sphere falling under the action of gravity in a stationary viscous fluid as:

$$\mu . v = 2/9 \; r^2 \; (\gamma_b - \gamma_s) \quad ..... \qquad (2.3)$$

where, μ = coefficient of viscosity,

v = steady velocity of the sinking of sphere,

r = radius of the sphere,

γ_b = unit weight of the body(sphere) and

γ_s = unit weight of fluid.

In obtaining μ, Barkan[2] did not consider the vibration given to the fluidised soil medium at all but latter based on experiments he gave the relationship between μ and acceleration of vibration as Fig. (2.6)

$$\frac{1}{\mu} = a \; (\eta - \eta_o) \quad .... \qquad (2.4)$$

a = constant factor,

η = ratio of acceleration of soil to the acceleration due to gravity,

η_o = the threshould acceleration ratio of the vibroviscous state of soil.

He showed from his experiments that when the acceleration of vibrations are lower than 1.5 g , the vibrations, practically do not affect the coefficient of viscosity.

2.4.5 Effect of Vibration on Porosity and Hydraulic Properties of Soil:

Barkan[2] describes this relationship for fine to medium grained sand on experimental evidence ~~Fig~~. (1.) as:

$$e = e_{min} + (e_{max} - e_{min}) \exp\left[-\alpha(\eta + \eta_o)\right] \quad \ldots \quad (2.5)$$

where,

e = void ratio at acceleration ratio, η

e_{max} = void ratio at the loosest state of soil,

e_{min} = minimum limit of the void ratio of the soil,

α = a value depending on moisture content to a maximum value between 0.82 to 0.88.

2.4.6 Effect of Surcharge and Confining Pressure:

Florin and Ivanov[12] say that liquefaction of sand depends upon surcharge weight also. They found out that soil below 15 m of ground surface hardly gets liquefied.

Kishida[18] after doing the extensive study at Niigata earthquake reported that soil is not likely to get liquefied if the value of confining pressure is more than 2 kg./sq.cm.

2.5 ACCELERATED MOTION OF SPHERE IN LIQUID:

Stokes investigated the simple hormonic and rectilinear oscillations of a sphere, a cylinder and an infinately long flat plate in a viscous fluid. He derived the expression for forces exerted by fluid on these objects. In arriving at this derivation he omitted convective acceleration terms in Navier Stokes Equation.

Later Basset[3] and Boussinesq studied the rectilinear motion of sphere which has a rapid but arbitrary acceleration in a viscous fluid. They say that the forces on the sphere depends not only on its instanteneous velocity and acceleration but also, on a term, which will be termed as Basset's "History Integral", which represents the effect of its entire history of acceleration.

Basset[3] presented the equation of motion (accelerated) of a sphere falling in a viscous fluid under the influence of gravity. He also assumed that for slow motions the squares and products of velocities, can be neglected. His equation reads as:

$$(m_s + km_f)\,\frac{dv_s}{dt} + 3\pi\mu\, dv_s + \frac{3}{2}\, d^2\sqrt{\pi\mu\rho_f}\int_0^t \frac{\frac{d}{d\tau}(v_s)\,d\tau}{(t-\tau)^{\frac{1}{2}}}$$

$$= (m_s - m_f)\,g \qquad \ldots. \qquad (2.6)$$

where,

m_s = mass of the sphere,

m_f = mass of the fluid displaced by sphere,

k = added mass coefficient (= ½ for sphere),

v_s = velocity of the sphere,

d = diameter of the sphere,

ρ_f = density of fluid,

τ = any time, $0 \leq \tau \leq t$

μ = coefficient of viscosity and

g = acceleration due to gravity.

The solution of the above equation was given by several persons like Basset[3], Brush[5], Hjelmfelt[14], Lord Rayleigh[31]. But each solution has got some limitations and also they cannot be applied to the case of an oscillating fluid.

The basic study of accelerated motion of a sphere in an oscillating fluid was due to Carsten[8] who obtained the solution making simplifying assumptions. The non-domensional form of the equation is :

$$\frac{d^2X}{dT^2} = S^* \text{Cos}\,(T/N_s^2) - P\,\frac{dX}{dT} - Q\,\text{Sin}\,(T/N_s^2) + M \qquad \ldots(2.7)$$

where,

T = dimensionless time factor = $\frac{\nu t}{d^2}$

S = a non dimensional constant = $\frac{P.RA}{N_s^2}$

N_s = a dimensionless constant equivalent to Stokes number $= \sqrt{\nu / wd^2}$

P = non dimensional constant = 18/(R+k)

Q = non dimensional constant $= \dfrac{1+k}{R+k} \cdot A/N_s^4$ and

M = non dimensional constant $= \dfrac{R-1}{R+k} \cdot B/N_s^4$.

Dasgupta[11] in his equation included the history integral term of Basset[3]. The equation is as follows:

$$m_s\ddot{x} = m_f\ddot{a} + km_f\,(\ddot{a} - \ddot{x}) + (m_s - m_f)g + 3\pi\mu d\,(\dot{a} - \dot{x})$$
$$+ \frac{3}{2} d^2\sqrt{\pi \rho_f \mu} \int_0^t \frac{\frac{d^2}{d\tau^2}(a - x)\,d\tau}{\sqrt{t-\tau}} \quad \ldots \qquad (2.8)$$

where,

a = position co-ordinate of fluid,

$\dot{a}$ = velocity co-ordinate of fluid,

$\ddot{a}$ = acceleration co-ordinate of fluid,

x = position co-ordinate of sphere,

$\dot{x}$ = velocity co-ordinate of sphere,

$\ddot{x}$ = acceleration co-ordinate of sphere,

ρ_s = mass density of the sphere,

ρ_f = mass density of the fluid,

m_f = mass of the valume of fluid displaced by the sphere,

μ = coefficient of vibro-viscosity ,

k = added mass coefficient of the sphere = 1/2 for sphere, and d = diameter of the sphere.

Dasgupta[11] found out the values of vibroviscosity with the analytical solution and compared these values with the values obtained from Stokes Solution. However, in this investigation for simplicity only Stokes Law has been adopted for the evaluation of vibroviscosity.

CHAPTER III

EXPERIMENTAL STUDIES

3.1 OBJECTIVE:

The present laboratory work was carried out with the following objectives:

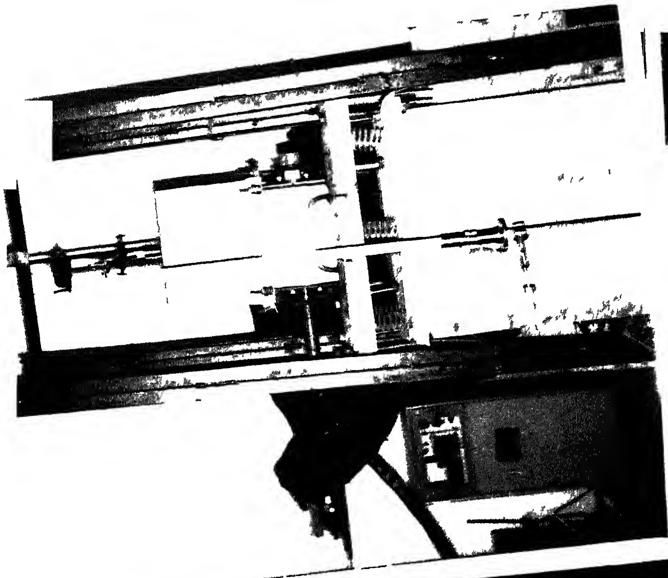
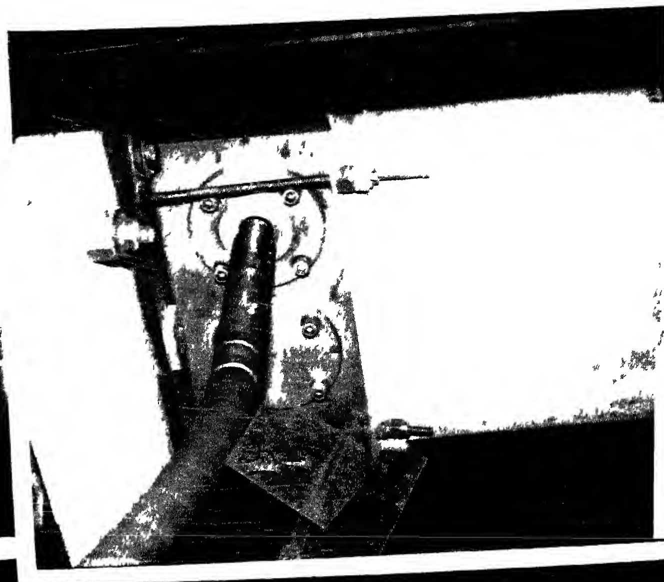
(i) To evaluate the coefficient of vibroviscosity when different body shapes are falling in the vibroviscous soil medium.

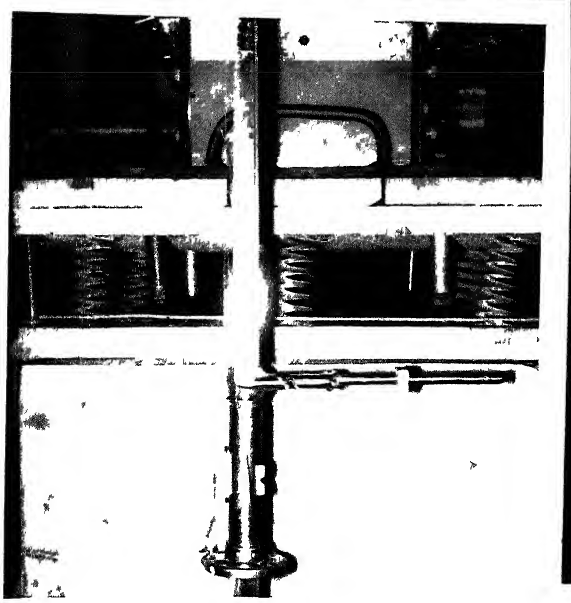
(ii) To see the effect of grain size, operating frequency, amplitude and acceleration of vibration, density at the liquefaction and surcharge weight etc. on vibroviscosity and sinking behaviour.

3.2 EXPERIMENTAL SET-UP:

The experimental set up is shown in Fig. (3.1) and also in photographs given . The details of the assembly are as follows:

On the concrete pedastal of dimensions 54 x 54 x 84 cms a wooden plank was kept and it was tied down to the pedastal by means of screws and hanging weights. In wooden plank six circular grooves of 4.5 cms diameter were made. Six springs of the same height are fixed in these grooves. To minimise their movement nails are put by the side of grooves. The exact position of springs is shown in the Fig. (3.2).




Similar arrangement of grooves is made in the top wooden plank which rests on springs. On this wooden plank an iron base plate 38 x 38 cms is put centrally. This plate is tied down to the wooden plank. The LA-oscillator rests on this base plate. The aluminium tank of the size 30 x 30 x25 cms is kept on this oscillator. To make the connection rigid this is tied to base plate by bolts and nuts.

A frame of angles and channels is fabricated. This is about 2 meters high. There is an angle iron which runs through the centre of the frame. Two frictionless pulleys are fixed on this angle. One is at the centre and one is at the end. A depth gauge is fixed near the pedestal. There is a counter weight which slides over the depth gauge which is graduated. The combination of the rod and counter weight makes the varnier arrangement as a result it is possible to measure the displacement of the counter weight upto 0.03mm . The counter weight is suspended from frictionless pulleys by non extensible silk thread. The other end of the thread goes to the stem of 3 m.m diameter through another pulley. The arrangement is made on the stem to keep the loads. These loads are imposed on the bodies of different shapes which are attached to the other end of stem. The bodies rest on the soil surface at the center of tank Fig.(3.1)

3.3 LA-OSCILLATOR:

3.3.1 General:

This is a mechanical type of vibrator operated by means of variable speed motor. The trade name of the oscillator is 'Lazan Oscillator'.

The maximum upward force given by this oscillator is ± 1600 lbs. and the maximum speed is 1800 rpm. It can give maximum torque of 4000 lb-in. at 1800 rpm.

3.3.2 Operation:

The oscillator utilizes the centrifugal force of unbalanced masses to generate the variable alternating force. Eccentric weights are unbalanced masses that generate the force. When the masses are out of phase through 180°, their centrifugal force cancels. While the force add up when they are in phase. This arrangement gives a force which acts in the single vertical plane. The magnitude of force depends on the phase angle between the small and large eccentricities. The arrangement is made in the oscillator to change the eccentric angle by force adjuster. The actual alternating force produced in lbs. from various angular settings is graphed in the operation manual.

3.4 VARIABLES IN THE TEST PROCEDURE:

The different variables which were studied during tests were (i) Time of sinking (ii) Shape of the object

(iii) Super imposed loads (iv) Grain size of the sand (v) Bulk density at liquefaction (vi) Frequency, amplitude and acceleration of vibration.

3.5 TESTING PROCEDURE:

The aluminium tank is filled with the Kalpi sand upto a certain level (the grain size distribution of the Kalpi sand is shown in Fig. 3.3).

Before conducting each test, sand is compacted by vibrating the soil for two minutes. Then the eccentricity is kept at certain angle by rotating the force adjuster of the oscillator. The frequency level is raised gradually by the knob until the sand starts liquefying. The frequency is noted. The object is kept in the centre of the tank on the soil surface. The initial reading of the depth gauge is noted. The the body is allowed to sink in the liquefied sand. At the same instant the stop watch is started. The depths of sinking of the body were noted on the depth gauge at every ½ , 1 , 2 , 3 , 4 , 5 , 6 , 8 , minutes time interval. After 8 minutes it was found that the sinking was quite negligible possibly due to proximity of the other end of the tank. The oscillator was stopped.

The test program was carried out using three grain sizes of the sand i.e. (i) passing through B.S. 14 and

retained on B.S. 36 (ii) Sand passing through B.S. 36 and retained on B.S. 52 (iii) Sand passing through B.S. 52 and retained on B.S. 72.

The tests were carried out at three diff rent frequencies and using four super imposed loads. Four different body shapes were tested. The complete details of the test series and shapes are given in Section 3.6 and 3.7 respectively.

3.6 TEST SERIES:

To study the falling of diffrernt body shapes in the vibroviscous medium and to have a feel of vibroviscosity of the soil, number of experiments were performed which can be grouped in three tests series namely T_1, T_2 and T_3. The following table gives the complete details of the tests carried out.

TABLE NO. 3.1

Test Series	Body Shape	Frequency in rpm	Super-imposed Loads in kg	Grain Size B.S. No.	Number of tests
T_1	S_1 big sphere	1050 1000 950	0.45 0.68 0.90 1.12	14-36 "	12

Test Series	Body Shape	Frequency in rpm	Super-imposed Loads kg	Grain Size B.S. Nos.	Number of Tests
	S_2 small sphere	1050 1000 950	0.45 0.68 0.90 1.12	14–36	12
	S_3 small cylinder with cone	1050 1000 950	0.45 0.68 0.90 1.12	14–36	12
	S_4 big cylinder with cone	1050 1000 950	0.45 0.68 0.90 1.12	14–36	12
	***			***	
T_2	S_1 big sphere	1050 1000 950	0.45 0.68 0.90 1.12	36–52	12
	S_2 small sphere	1050 1000 950	0.45 0.68 0.90 1.12	36–52	12

Test Series	Body Shape	Frequency in rpm	Super-imposed Loads kg	Grain Size B.S. Nos.	Number of Tests
	S_3 small cylinder with cone	1050 1000 950	0.45 0.68 0.90 1.12	36-52	12
	S_4 big cylinder with cone	1050 1000 950	0.45 0.68 0.90 1.12	36-52	12
T_3	S_1 big sphere	1050 1000 950	0.45 0.68 0.90 1.12	52-72	12
	S_2 small sphere	1050 1000 950	0.45 0.68 0.90 1.12	52-72	12
	S_3 small cylinder with cone	1050 1000 950	0.45 0.68 0.90 1.12	52-72	12
	S_4 big cylinder with cone	1050 1000 950	0.45 0.68 0.90 1.12	52-72	12

3.7 BODY SHAPE DETAILS:

There are in all four body shapes which were used in tests series Fig. (3.2). All the bodies shapes are made out from brass. Their exact dimensions and other properties are given in the following table.

TABLE NO. 3.2

Nomenclature	Body Shape	Length cms	Diameter cms	θ Degrees	Mass gms.	Density gms/cc	Material
S_1	Big Sphere	-	3	-	119.7	8.45	Brass
S_2	Small Sphere	-	2.5	-	70.30	8.45	Brass
S_3	Small Cyli. with Cone	Total: 7 Cyli.: 5 Cone: 2	1.5	40°	81.75	8.45	Brass
S_4	Big Cyli. with Cone	Total: 10.5 Cyli.: 9 Cone: 1.5	2.0	60°	296.30	8.45	Brass

3.8 SOIL CHARACTERISTICS:

The soil which was used in all the experiments is Kalpi Sand. The grain size distribution curve of the sand is shown in Fig. (3.3). The density of the sand was found to be 1.72 gms/cc. maximum. Minimum density was 1.4 gms/cc. Maximum density in air dry state was 1.67 gms/cc. . The angle of internal friction varies from 27° (minimum) to 36° (maximum) . The void ratio in the loosest possible

state i.e. e_{max} is 0.82 and in densest possible state is e_{min} 0.48.

The experimental observations and results have been discussed in the next Chapter and are presented in graphs.

THAPTER IV

DIMENSIONAL ANALYSIS AND TEST RESULTS

4.1 PROBLEM:

The basic parameters which are involved in the study of falling of different bodies in vibroviscous medium may be grouped in the from of the relationship (4.1) given below,

$$S = f_1 \left(t, \text{Body Geomatry}, a_o, d_p, \omega, \text{Sphericity}^{*}, \text{particle shape}, \rho_{body}, \rho_{bulk\ static} \right) \qquad (4.1)$$

in which

S = Depth of sinking

t = Time of sinking

a_o = Amplitude of vibration

d_p = Particle size

ω = Frequency of vibration

ρ_{body} = Density of body

ρ_{bulk} = Bulk density of sand

But μ, the vibroviscosity of soil and ρ_{bulk} (vibrated condition) will be affected by the parameters a_o, d_p, ω, sphericity and particle shape and hence the latter variables alongwith $\rho_{bulk(static)}$ may be replaced by μ and $\rho_{bulk(vibrated\ condition)}$.

So writing the equation (4.1) as:

$$S = f_2 \left(t, \text{Body shape}, \underset{L,\,D,\,\theta}{\underline{\text{Body dimensions}}}, \mu, F, \rho_{body}, \rho_{bulk(vibrated\ condition)} \right.$$

---

* Sphericity : It has been defined as the ratio of surface area of sphere with the same volume as the grain to the surface area of particle.

4.2 BUCKINGHAM π THEOREM:

"If n quantities are required to describe some physical phenomenon, and if these quantities involve m dimensional categories, the relationship can be reduced to one comprising of n - r non dimensional products, $r \leq m$ being the rank of n x m dimensional matrix "[33].

Thus, if

$$f (A_1 , A_2 , A_3 , \ldots A_n) = 0 \ldots \qquad (4.2)$$

The theorem states that these n dimensional variables can be combined into an equally valid expression involving r fewer terms.

$$F (\pi_1, \pi_2, \ldots \pi_{n-r}) = 0 \ldots \qquad (4.3)$$

4.3 DIMENSIONAL ANALYSIS:

So writing equation (4.1)

$$S = f_1(t, \text{Body shape}, L, D, \theta, \mu, F, \text{body part.}) \ldots \qquad (4.4)$$

No. of π terms = n-m

= 10-3 = 7

In the above quation,

Body shape is non dimensioal $= \pi_1$

θ is also non dimensional $= \pi_2$

Using MLT system and writing the mathematical statement of dimensional homogeneity,

$$M^oL^oT^o = (S)^{a_1} (t)^{a_2} (L)^{a_3} (D)^{a_4} (\mu)^{a_5} (F)^{a_6} (\rho_b)^{a_7} (\rho_p)^{a_8} \ldots \qquad (4.5)$$

Substituting the dimensional equivalents,

$$M^oL^oT^o = (L)^{a_1}(T)^{a_2}(L)^{a_3}(L)^{a_4}(M/LT)^{a_5}(ML/T^2)^{a_6}(M/L^3)^{a_7}(M/L^3)^{a_8} \quad \ldots \quad (4.6)$$

Rearranging to,

$$M^oL^oT^o = M^{a_5+a_6+a_7+a_8} \, L^{a_1+a_3+a_4-a_5+a_6-3a_7-3a_8} \, T^{a_2-a_5-2a_6} \quad \ldots \quad (4.7)$$

Equating the exponents of MLT to get,

$$M : 0 = a_5+a_6+a_7+a_8 \quad \ldots \quad (4.8)$$

$$L : 0 = a_1+a_3+a_4-a_5+a_6-3a_7-3a_8 \quad \ldots \quad (4.9)$$

$$T : 0 = a_2-a_5-2a_6 \quad \ldots \quad (4.10)$$

Solving the equations (4.8), (4.9) and (4.10) for three constant a_4, a_5, a_8, to get,

$$a_5 = a_2 - 2a_6 \quad \ldots \quad (4.11)$$

$$a_8 = -a_2 + a_6 - a_7 \quad \ldots \quad (4.12)$$

$$a_4 = - a_1 - a_3 - 2a_2 \quad \ldots \quad (4.13)$$

Subsituting the values in equation (4.5) to get,

$$M^oL^oT^o = (S)^{a_1} (t)^{a_2} (L)^{a_3} (D)^{-a_1-a_3-2a_2} (\mu)^{a_2-2a_6} (F)^{a_6} (\rho_b)^{a_7} (\rho_p)^{-a_2+a_6-a_7} \quad \ldots \quad (4.14)$$

Collecting the terms with the same exponent gives,

$$M^oL^oT^o = (S/D)^{a_1} \left(\frac{\mu t}{\rho_p D^2}\right)^{a_2} (L/D)^{a_3} \left(\frac{F \rho_p}{\mu^2}\right)^{a_4} \left(\frac{\rho_b}{\rho_p}\right)^{a_5} \quad \ldots \quad (4.15)$$

These terms are dimensionless, π terms,

$$\pi_3 = S/D \, , \; \pi_4 = \frac{\mu t}{\rho_p D^2} \, , \; \pi_5 = L/D \, , \; \pi_6 = \frac{F \rho_p}{\mu^2} \, , \; \pi_7 = \frac{\rho_b}{\rho_p}$$

Therefore,

$$F(\text{Body shape}, \theta, S, t, L, D, \mu, F, \rho_b, \gamma_p) \overset{=0}{\&} f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7) = 0 \qquad \ldots\ldots \quad (4.16)$$

The dimensionless graphs are drawn between S/D versus $\frac{\mu t}{\rho_p D^2}$ for different values of $\frac{F \gamma_p}{\mu^2}$ keeping other parameters constant. These graphs are shown in Figs. (4.1, 4.2, 4.3).

4.4 VIBROVISCOSITY:

The experiments show that when sand sample is subjected to intense vibrations, the forces of internal dry friction between the particles vanish and assume the mechanical properties of viscous fluid. Thus, the solid bodies placed on this sand will sink into it with certain velocity if their density exceeds the density of sand. The mechanical property of sand is designated as vibroviscosity.

4.5 OBJECT OF EXPERIMENTAL STUDIES:

The main object of the experiments carried out so far is:

(i) To determine sinking of different bodies in vibroviscous sand medium and effect of different parameters on sinking behaviour.

(ii) To find out vibroviscosity μ by Stokes solution and to see the effects of different pa meters on μ

4.6 STOKES SOLUTION:

If a spherical body descends through a semi infinite viscous fluid with velocity v, as per Stokes Law:

The viscous drag $3\pi\mu dV$ is equal to bo$\overset{u}{\wedge}$yant force $(m_s - m_f)g$. The terms have already been explained in Chapter

Thus,

Down ward force = B$\overset{u}{\wedge}$oyant force + Resisting force .. (4.17)

$$F + \frac{\pi d^3}{6}\rho_b \cdot g = \frac{\pi d^3}{6}\rho_s \cdot g + 3\pi\mu dV \quad \ldots \quad (4.18)$$

Therefore,

$$3\pi\mu dV = \frac{\pi}{6} d^3 g(\rho_b - \rho_s) + F \quad \ldots \quad (4.19)$$

It will assumed that the load on the upper disc will only increase the density of the body in the following way,

If F is the superimposed load acting on the body in addition to its own weight, and if γ_E is the equivalent increase of unit weight, then,

$$\gamma_E = \frac{6F}{\pi d^3} \quad \ldots \quad (4.20)$$

and actual γ_b will be,

$$\gamma_b = \gamma_b' + \gamma_E \quad \ldots. \quad (4.21)$$

where γ_b' is the actual unit weight of the body shape. From the equation (4.19),

$$\mu = \frac{d^2 (\gamma_b - \gamma_s)}{18 V} \quad .... \quad (4.22)$$

Using this relation and utilizing the velocity of fall of different bodies the vibroviscosity was found out. The shapes S_3 and S_4 are converted into equivalent sphere of diameter of equal volume of the body shape. The values of vibroviscosity are given in Table (4.1).

The graphs between vibroviscosity and acceleration of vibration, vibroviscosity versus grain size were also plotted for all body shapes. Figs. (4.4, 4.5, 4.6, 4.7A, 4.7B, 4.7C) .

4.7 SAMPLE CALCULATION:

The sample calculation for finding the value of vibroviscosity is given below:

Body shape	:	Big sphere
Superimposed Load	=	0.45 kg.
Frequency	=	1050 rpm
Acceleration of Vibration	=	0.85 g
Sand	:	Passing through B.S. 14 and retaind on B.S. 36
Diameter	=	3 cms.
d^2	=	9 cms.

$$\gamma_s = 1.43 \text{ gms/cc.}$$

$$\gamma_b' = 8.45 \text{ gms/cc.}$$

$$\gamma_E = 6F/\pi d^3$$

$$= \frac{6 \times 453.6}{\pi \times 27} = 32.05 \text{ gms/cc}$$

$$\gamma_b = \gamma_b' + \gamma_E$$

$$= 8.45 + 32.05 = 40.5 \text{ gms/cc.}$$

$$V = 0.31/60 \text{ cms/sec.} \quad (\text{from S versus t graph})$$

$$\mu = \frac{d^2 (\gamma_b - \gamma_s)}{18 V}$$

$$= \frac{9 (40.5 - 1.43) \times 60 \times 100}{18 \times 31}$$

$$= 3.78 \times 10^3 \text{ gms.sec./cm}^2$$

$$= 3.78 \text{ kg sec./cm.}^2$$

4.8 DENSITY MEASUREMENTS:

The bulk density of the soil at liquefaction was measured by following technique:

Eight containers were placed in sand at two different levels in the tank. Four containers are kept at four corners. The soil in the tank was vibrated at a particular frequency for some time with container in side the sand. Then vibrations are stopped and the containers are taken out carefully. They are weighed and the density was found out. These readings are taken for every frequency level and for each grain size of the sand.

4.9 VISICORDER RECORDS:

To know the maximum amplitude, velocity and acceleration of vibration at particular frequency visicorder was used. M.B. Electronics vertical pick up was fixed on the platform and the readings were noted.

4.10 SINKING BEHAVIOUR:

To study the sinking behaviour of different body shapes graphs were plotted between S versus t for a particular test series Figs.(4.8, 4.9 and 4.10). To see the effect of different parameters e.g. (i) grain size (ii) density of the deposit at liquefaction(iii) acceleration of vibration (iv) surcharge weight on sinking behaviour graphs were drawn between S and t Figs. (4.11 to 4.19).

TABLE 4.1

Experimental Values of Vibroviscosity
Big Sphere

Load kgs.	Frequency rpm	Acceleration of Vibration g	Grain Size B.S. Nos.	Vibro-viscosity $kgs.sec/cm^2$
0.45	1050	0.85	52-72	7.79
0.68	"	"	"	8.19
0.90	"	"	"	9.00
1.12	"	"	"	9.72
0.45	1000	1.0	52-72	8.13
0.68	"	"	"	8.52
0.90	"	"	"	9.38
1.12	"	"	"	10.08
0.45	950	1.2	52-72	8.62
0.68	"	"	"	9.05
0.90	"	"	"	9.90
1.12	"	"	"	10.62
0.45	1050	0.85	36-52	5.82
0.68	"	"	"	6.50
0.90	"	"	"	7.05
1.12	"	"	"	7.25
0.45	1000	1.0	36-52	6.15
0.68	"	"	"	6.92
0.90	"	"	"	7.41
1.12	"	"	"	7.64
0.45	950	1.2	36-52	6.70
0.68	"	"	"	7.39
0.90	"	"	"	7.80
1.12	"	"	"	8.14
0.45	1050	0.85	14-36	3.78
0.68	"	"	"	5.57
0.90	"	"	"	4.85
1.12	"	"	"	5.45
0.45	1000	1.0	14-36	4.12
0.68	"	"	"	4.87
0.90	"	"	"	5.25
1.12	"	"	"	5.74
0.45	950	1.2	14-36	4.45
0.68	"	"	"	5.32
0.90	"	"	"	5.76
1.12	"	"	"	6.20

Small Sphere

Load kgs.	Frequency rpm	Acceleration of Vibration g	Grain Size B.S. Nos.	Vibro-viscosity $kgs.sec/cm^2$
0.45	1050	0.85	52-72	7.86
0.68	"	"	"	8.24
0.90	"	"	"	8.95
1.12	"	"	"	9.72
0.45	1000	1.0	52-72	8.10
0.68	"	"	"	8.47
0.90	"	"	"	9.44
1.12	"	"	"	10.16
0.45	950	1.2	52-72	8.53
0.68	"	"	"	9.00
0.90	"	"	"	9.81
1.12	"	"	"	10.69
0.45	1050	0.85	36-52	5.84
0.68	"	"	"	6.44
0.90	"	"	"	7.10
1.12	"	"	"	7.35
0.45	1000	1.0	36-52	6.19
0.68	"	"	"	7.00
0.90	"	"	"	7.36
1.12	"	"	"	7.68
0.45	950	1.2	36-52	6.66
0.68	"	"	"	7.41
0.90	"	"	"	7.92
1.12	"	"	"	8.09
0.45	1050	0.85	14-36	3.82
0.68	"	"	"	4.51
0.90	"	"	"	4.82
1.12	"	"	"	5.37
0.45	1000	1.0	14-36	4.06
0.68	"	"	"	4.90
0.90	"	"	"	5.18
1.12	"	"	"	5.75
0.45	950	1.2	14-36	4.48
0.68	"	"	"	5.32
0.90	"	"	"	5.70
1.12	"	"	"	6.28

Small Cylinder with Cone

Load kgs.	Frequency rpm	Acceleration of Vibration g	Grain Size B.S. Nos.	Vibro-viscosity kgs.sec/cm^2
0.45	1050	0.85	52-72	4.16
0.68	"	"	"	4.48
0.90	"	"	"	5.18
1.12	"	"	"	5.39
0.45	1000	1.0	52-72	4.62
0.68	"	"	"	4.90
0.90	"	"	"	5.64
1.12	"	"	"	5.86
0.45	950	1.2	52-72	5.15
0.68	"	"	"	5.50
0.90	"	"	"	6.25
1.12	"	"	"	6.51
		***	***	
0.45	1050	0.85	36-52	3.48
0.68	"	"	"	3.75
0.90	"	"	"	4.00
1.12	"	"	"	4.75
0.45	1000	1.0	36-52	3.84
0.68	"	"	"	4.22
0.90	"	"	"	4.50
1.12	"	"	"	5.27
0.45	950	1.2	36-52	4.44
0.68	"	"	"	4.84
0.90	"	"	"	5.03
1.12	"	"	"	5.91
		***	****	
0.45	1050	0.85	14-36	2.19
0.68	"	"	"	2.65
0.90	"	"	"	3.15
1.12	"	"	"	3.58
0.45	1000	1.0	14-36	2.58
0.68	"	"	"	3.10
0.90	"	"	"	3.50
1.12	"	"	"	4.06
0.45	950	1.2	14-36	3.14
0.68	"	"	"	3.70
0.90	"	"	"	4.08
1.12	"	"	"	4.63

Big Cylinder with Cone

Load kgs.	Frequency rpm	Acceleration of Vibration g	Grain Size B.S. Nos.	Vibro-viscosity, kgs.sec/cm
0.45	1050	0.85	52-72	3.78
0.68	"	"	"	4.53
0.90	"	"	"	5.11
1.12	"	"	"	5.80
0.45	1000	1.0	52-72	4.02
0.68	"	"	"	4.86
0.90	"	"	"	5.42
1.12	"	"	"	6.00
0.45	950	1.2	52-72	4.30
0.68	"	"	"	5.17
0.90	"	"	"	5.78
1.12	"	"	"	6.50
		** **	**	
0.45	1050	0.85	36-52	2.33
0.68	"	"	"	2.81
0.90	"	"	"	3.54
1.12	"	"	"	4.01
0.45	1000	1.0	36-52	2.53
0.68	"	"	"	3.01
0.90	"	"	"	3.83
1.12	"	"	"	4.24
0.45	950	1.2	36-52	2.86
0.68	"	"	"	3.26
0.90	"	"	"	4.16
1.12	"	"	"	4.55
		***	***	
0.45	1050	0.85	14-36	1.65
0.68	"	"	"	1.90
0.90	"	"	"	2.15
1.12	"	"	"	2.42
0.45	1000	1.0	14-36	1.83
0.68	"	"	"	2.13
0.90	"	"	"	2.40
1.12	"	"	"	2.68
0.45	950	1.2	14-36	2.03
0.68	"	"	"	2.33
0.90	"	"	"	2.66
1.12	"	"	"	2.96

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS FROM EXPERIMENTAL RESULTS:

Experiments have been conducted in this investigation to study the falling of different bodies in vibroviscous soil medium. The effect of grain size, frequency, acceleration of vibration, density of the soil on the falling of different bodies was also studied and graphically presented. The vibroviscosity of the fluidised soil medium has been evaluated by changing the parameters like grain size, frequency and acceleration of vibration, sizes and shapes of objects.

The graphs were plotted between S versus t for different bodies to compare their sinking behaviour Figs. (4.8, 4.9 and 4.10). They show that for pile like objects the sinking was much more than spheres in the same interval of time. The slope of S versus t curve also increases which means that velocity of sinking is also increasing in case of these bodies.

To show the effect of different parameters such as (i) grain size of the particles (ii) density of the soil at liquefaction (iii) acceleration of vibration (iv) surcharge weight on sinking behaviour of the bodies, the graphs between S and t were plotted in Figs. (4.11 to 4.19).

From these graphs are following qualitative observations can be made:

(i) When the grain size of the particles is bigger, the sinking of the bodies and the velocity of sinking is more for all bodies, Figs. (4.11 and 4.12).

(ii) For every frequency of vibration the density at liquefaction is changing. For higher frequencies of vibration the density is less. The sinking of all bodies and the velocity of sinking is more when the density at the time of liquefaction becomes less and less Figs. (4.13, 4.14 and 4.15).

(iii) Within the range of acceleration of vibration recorded it was observed that when the acceleration of vibration decreases the sinking of the bodies and the velocity of sinking increases. The increase is not much Figs. (4.16 and 4.17).

(iv) For higher surcharge weights the velocity of sinking is more Figs. (4.18 and 4.19).

Within the acceleration range tested the graphs between the acceleration of vibration and vibroviscosity were plotted for different bodies Figs. (4.4, 4.5 and 4.6). These graphs show that there is almost a straight line relationship between the acceleration of vibration η and vibroviscosity μ . When acceleration of vibration increases the values of vibroviscosity also increase.

Barkan[2] says that there is a sharp decrease in the values of vibroviscosity after the acceleration of vibration reaches the value of 1.5 g. But in the experiments conducted the maximum value of acceleration of vibration was limited to 1.2 g due to practical considerations.

The graphs between the vibroviscosity and the grain size of the particles were plotted for different surcharge loads Figs. (4.7A, 4.7B and 4.7C). They show that when the grain size of particles decreases the value of vibroviscosity increases. The pattern is nearly same for all bodies.

The dimensional analysis was carried out to generilise the results of experiments. The graphs between S/D versus $\frac{\mu t}{\rho_p D^2}$ were plotted for different values of $F \rho_p / {}^2$ The graphs are also presented for diffierent values of L/D and θ. These graphs show that S/D values are higher for higher $\frac{F \rho_p}{D^2}$ and $\frac{\mu t}{\rho_p D^2}$ values are less for higher $\frac{F \rho_p}{2}$ values, Figs. (4.1 to 4.3).

5.2 RECOMMENDATIONS:

In the experiments conducted, the dry sand was used for testing purposes. The vibroviscosity was found out by Stokes solution which can only be used for spherical shapes. The experiments can be performed and analytical solutions

can be formed which will give exact value of vibroviscosity for all body shapes taking into consideration all the forces and finding equivalent spheres which will give similar characteristics.

Effect of water content, (saturated soils or partially saturated soils) on the sinking behaviour of objects can be studied experimentally. Experiments on various types of soils with cohesion (cohesive soils) also form an important aspect of this study. The experimental observations under various other modes of vibration such as horizontal translation, etc. may be experimentally investigated.

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(AFTER BARKAN, 1960)

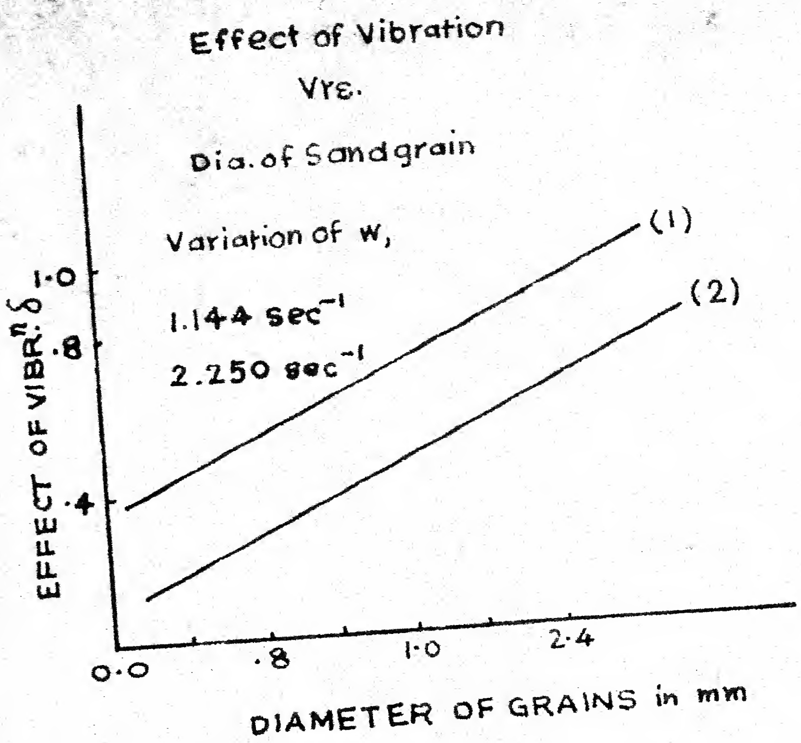


FIG. 2·3

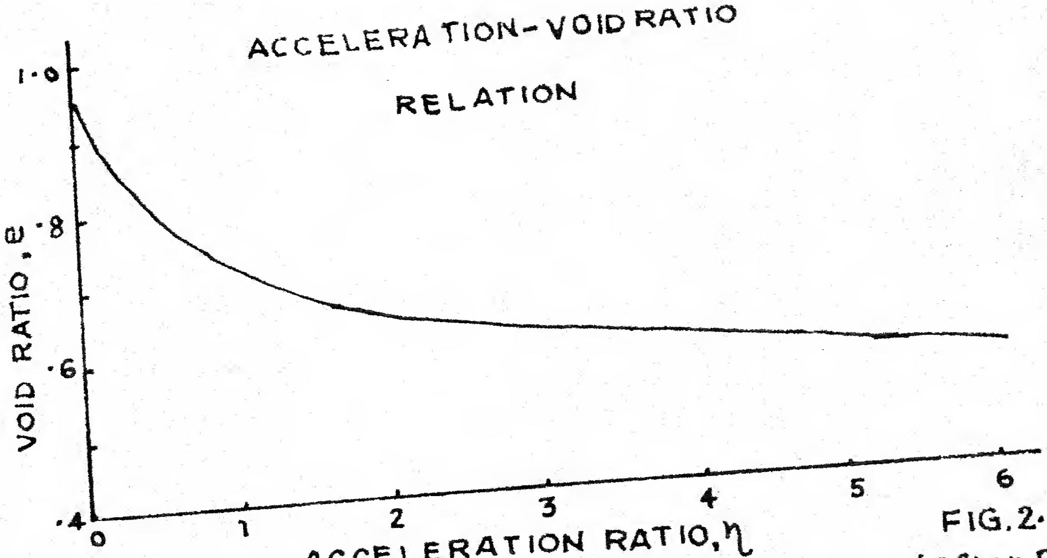


FIG. 2·1
(After BARKAN), 1960

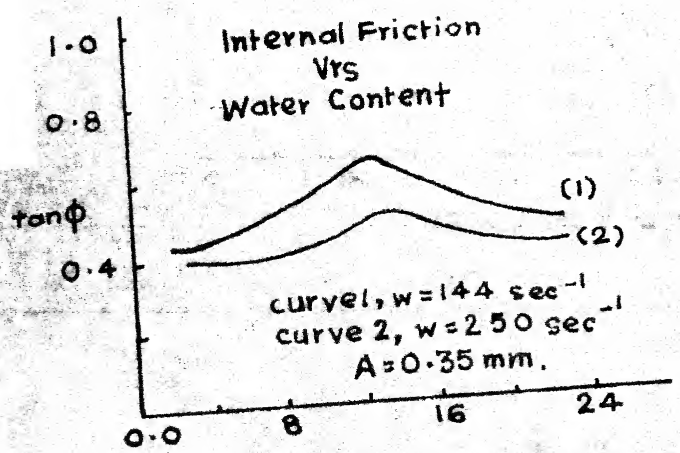


FIG. 2·2

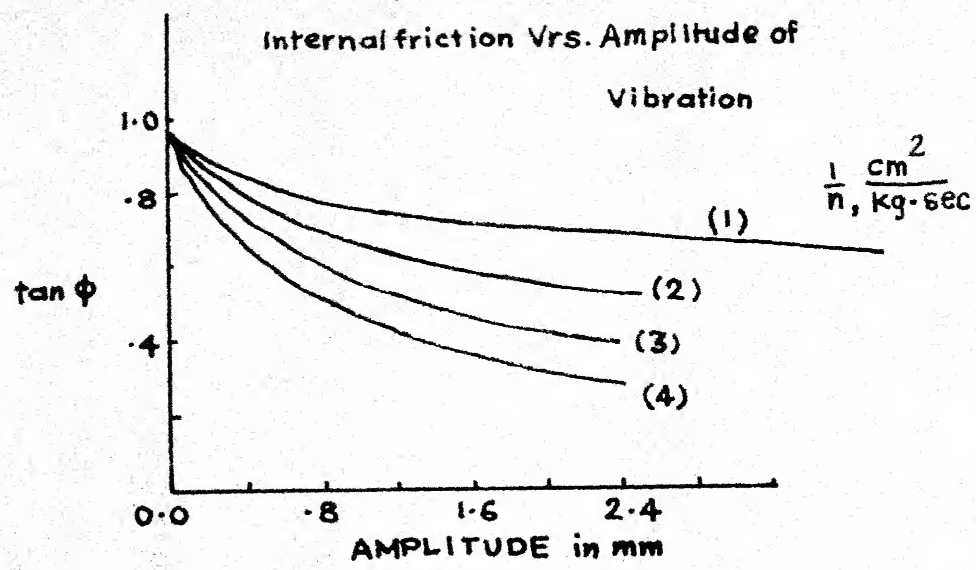
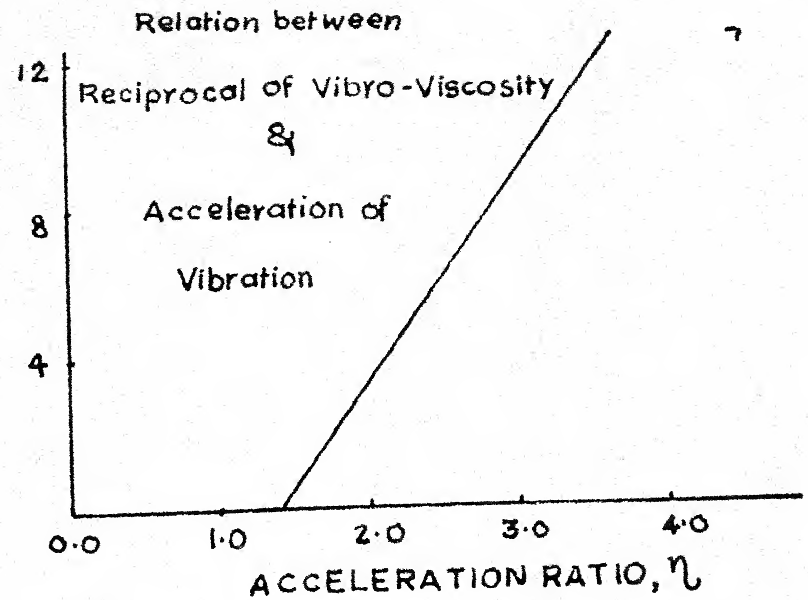


FIG - 2.5



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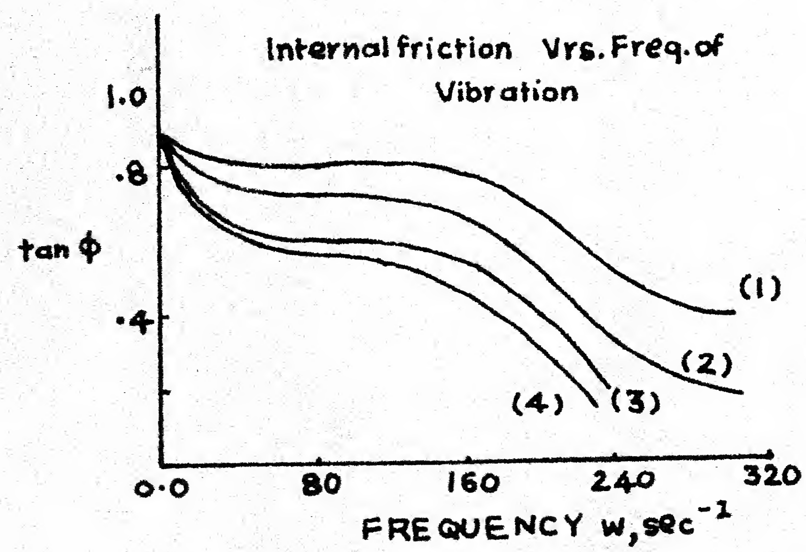

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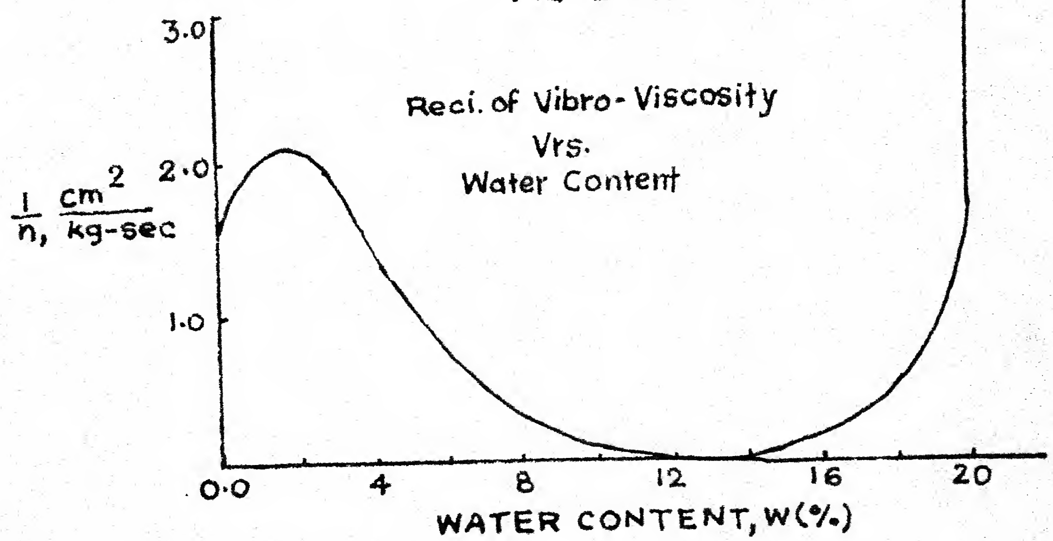


FIG - 2.7

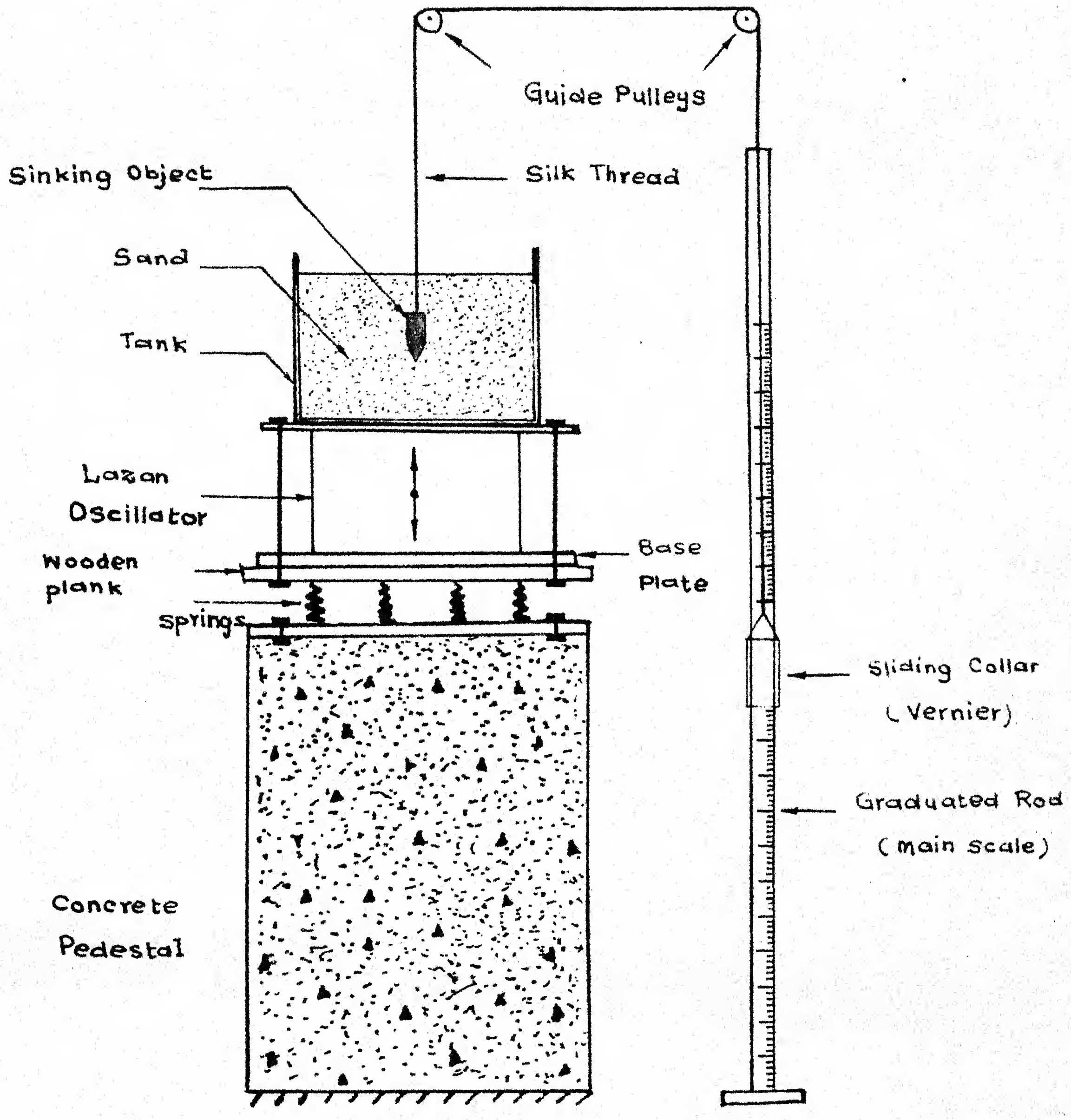


FIGURE : 3.1 -

EXPERIMENTAL SETUP

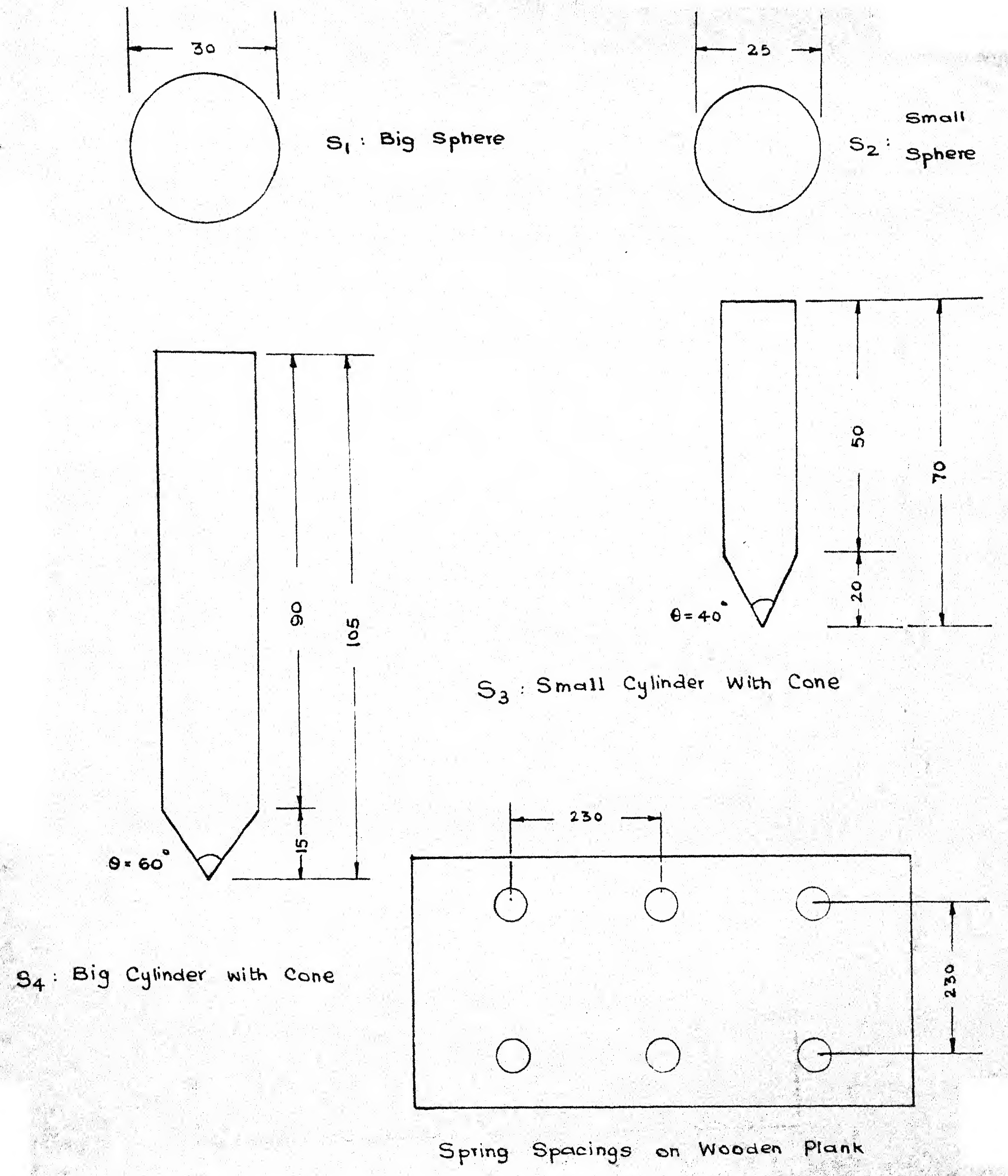


FIGURE 3.2 : DETAILS OF BODY SHAPE AND SPRING BASE

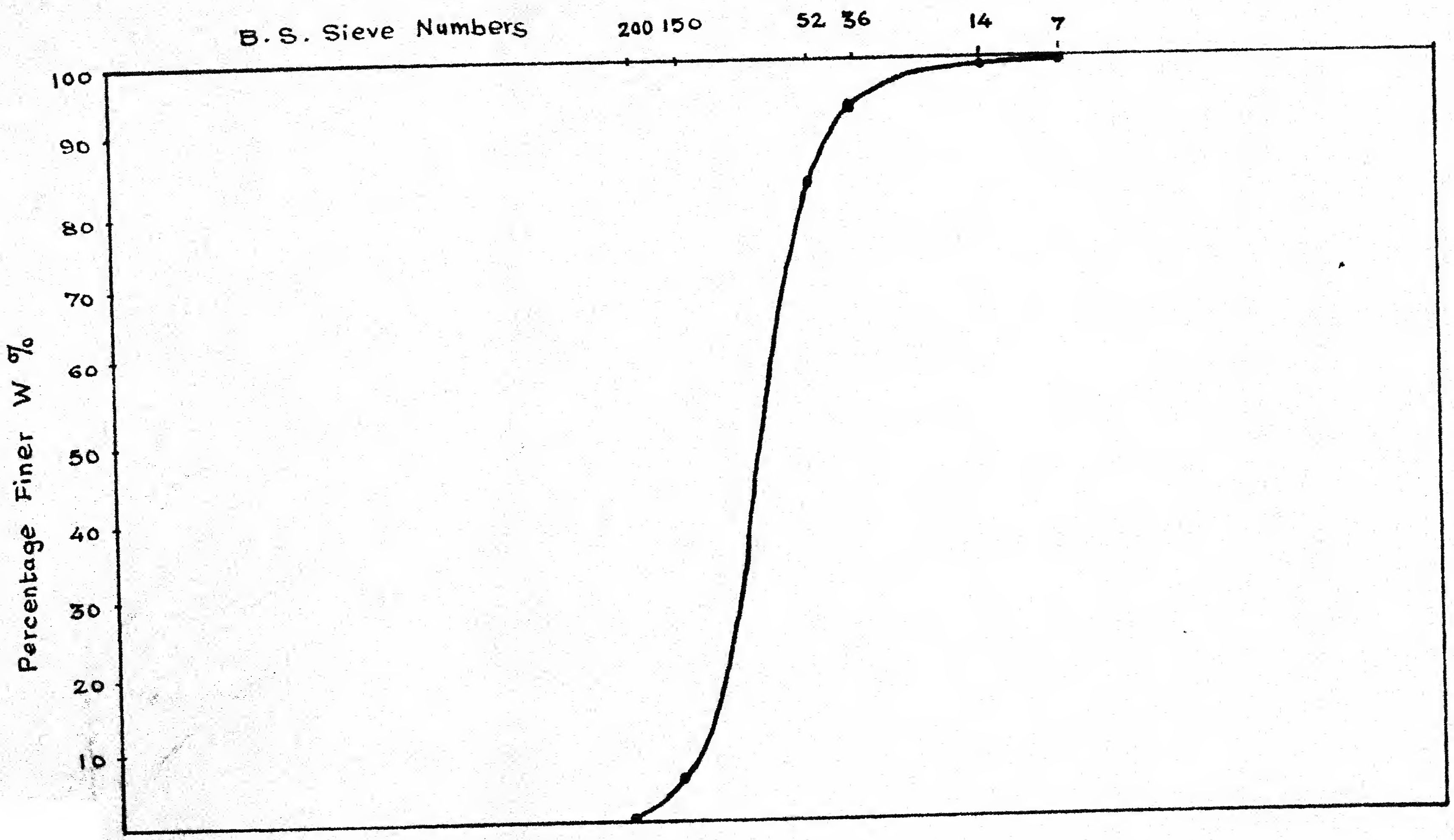
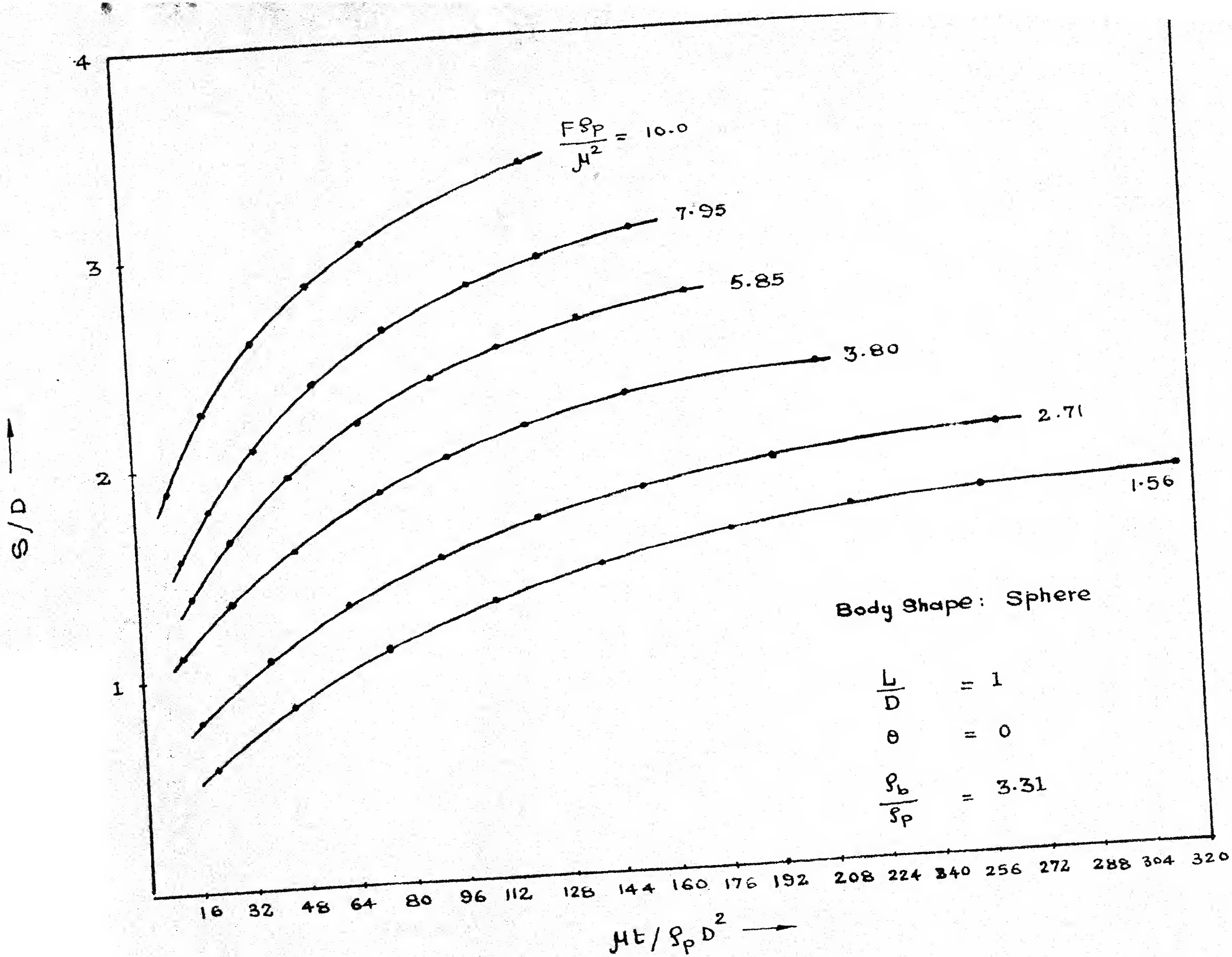
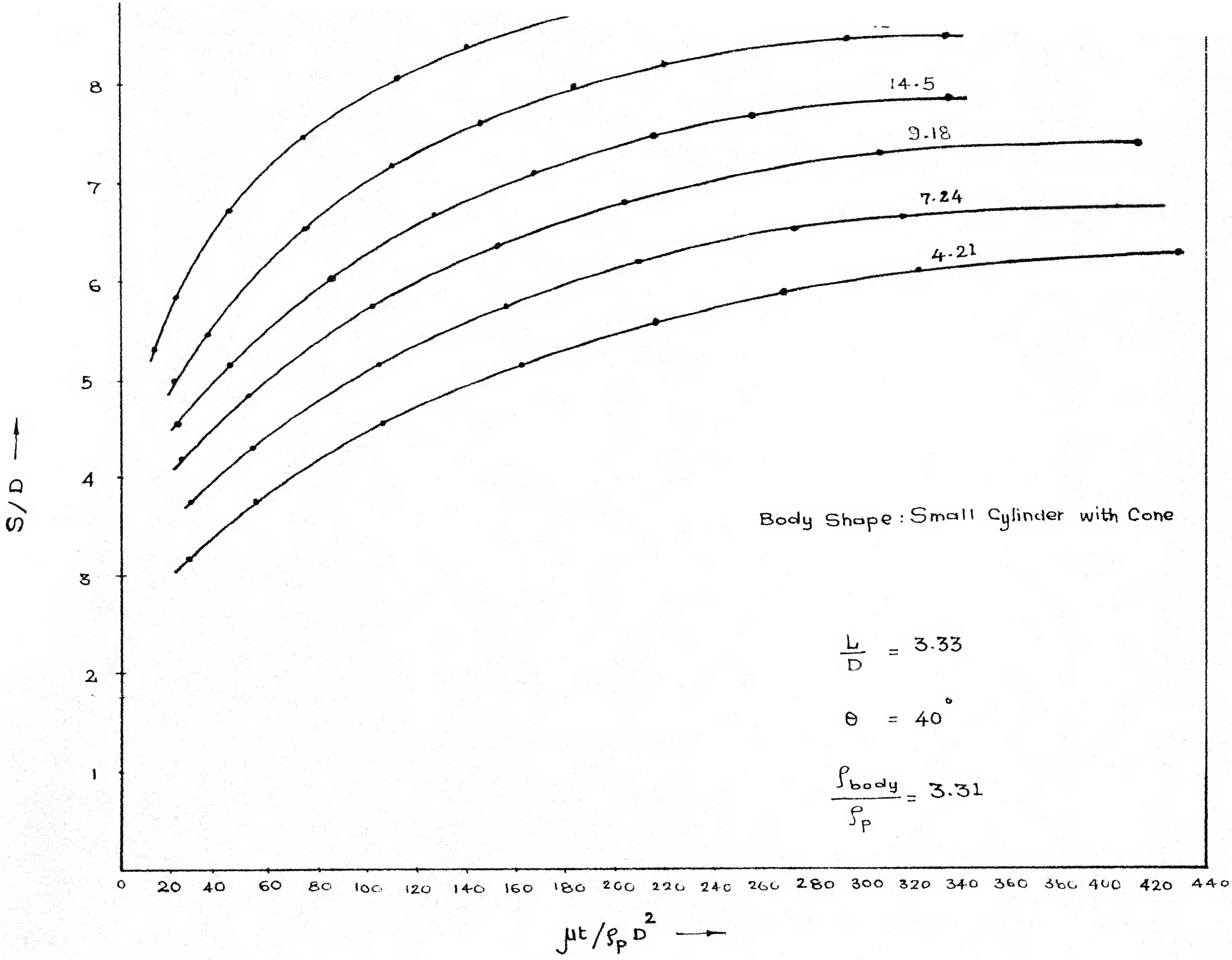


FIGURE 3.3 : GRAIN SIZE DISTRIBUTION CURVE



...URE 4.1 : NON-DIMENSIONAL PLOT OF S/D VS. $\mu t / \rho_p D^2$



PLOT OF S/D VS $\mu t/\rho_p D^2$

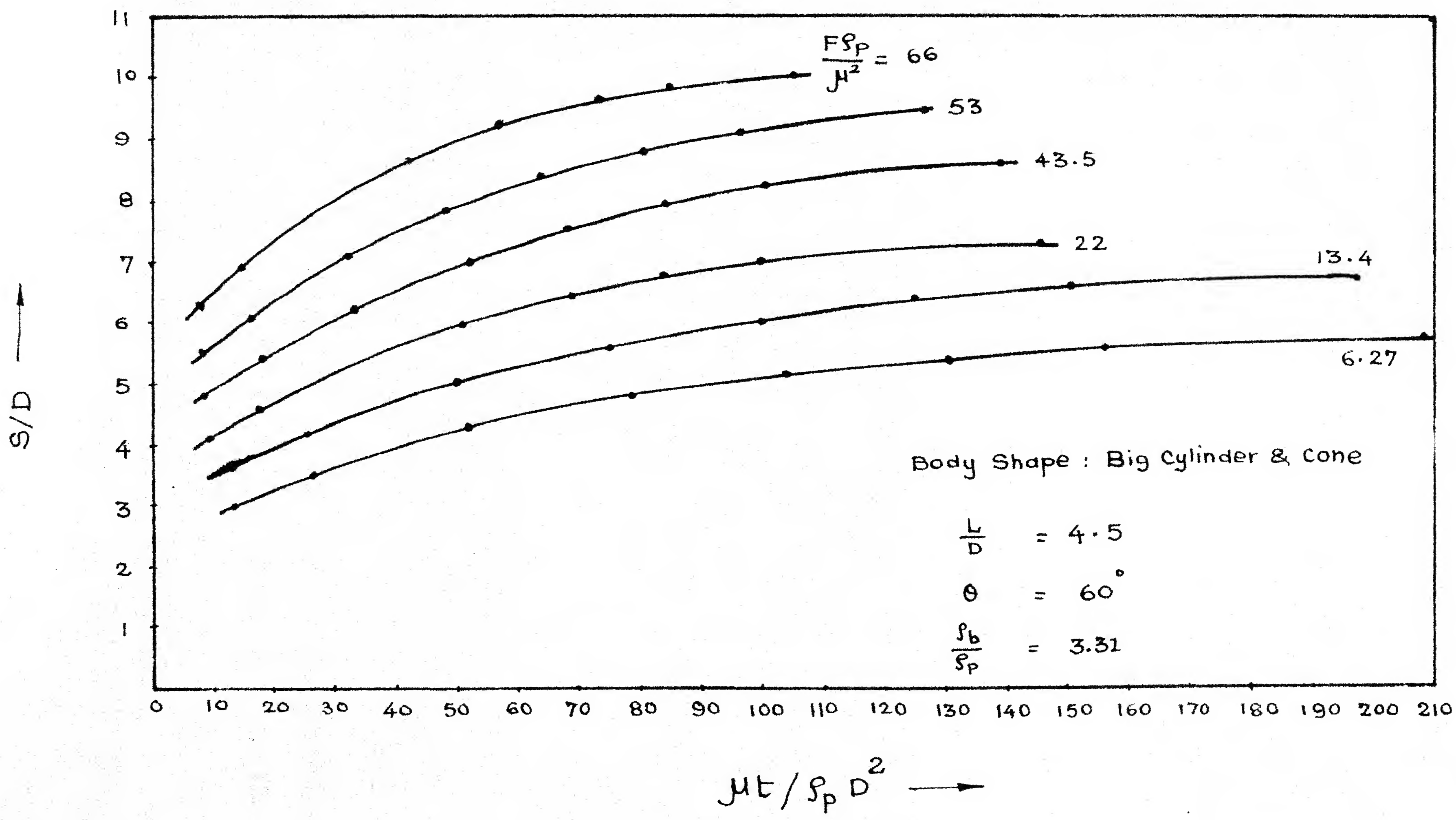


FIGURE 4.3 : NON-DIMENSIONAL PLOT OF S/D VS. $\mu t/\rho_p D^2$

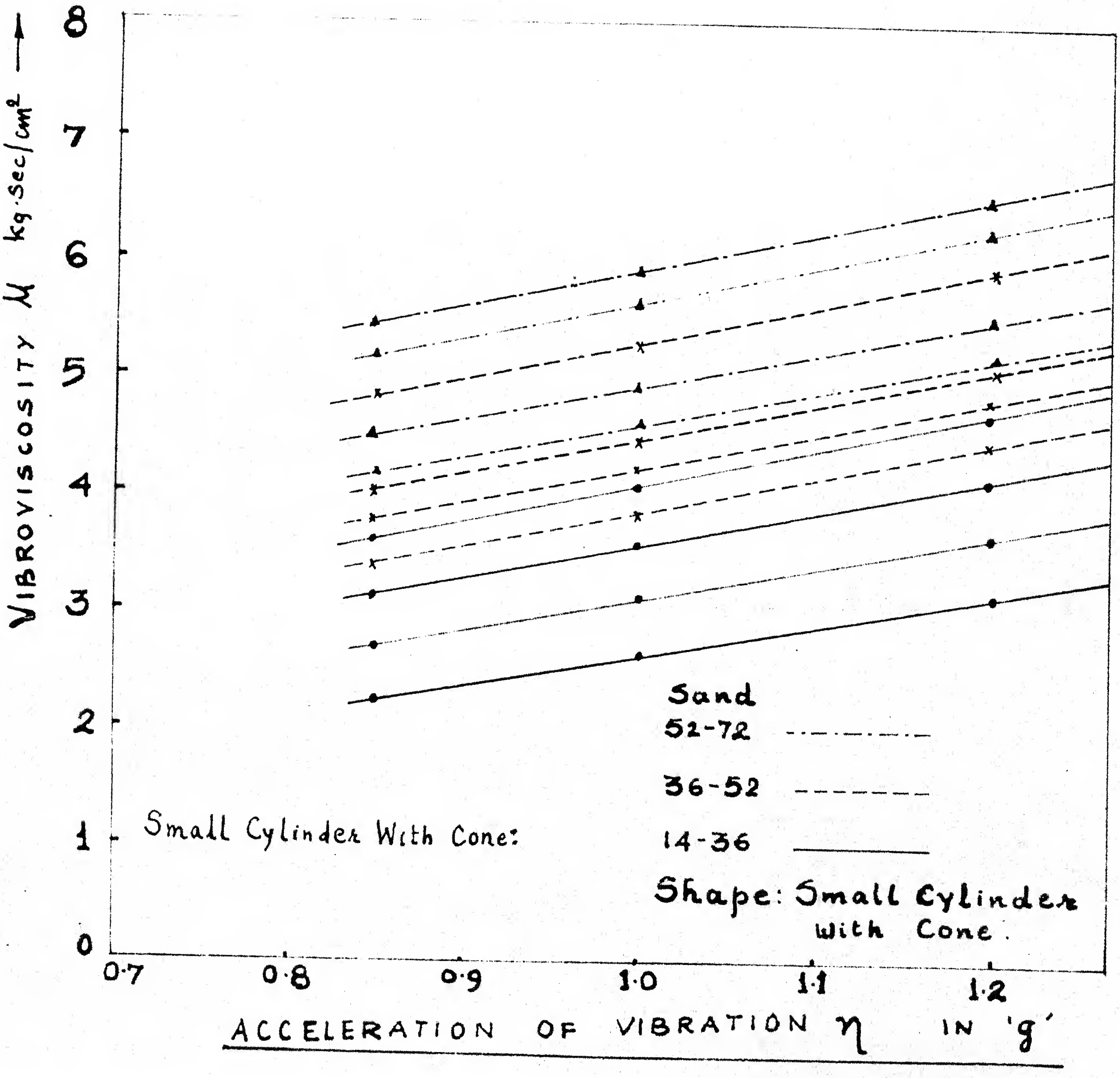


FIGURE 4·5 : EFFECT OF ACCN. OF VIB. ON VIBROVISCOSITY

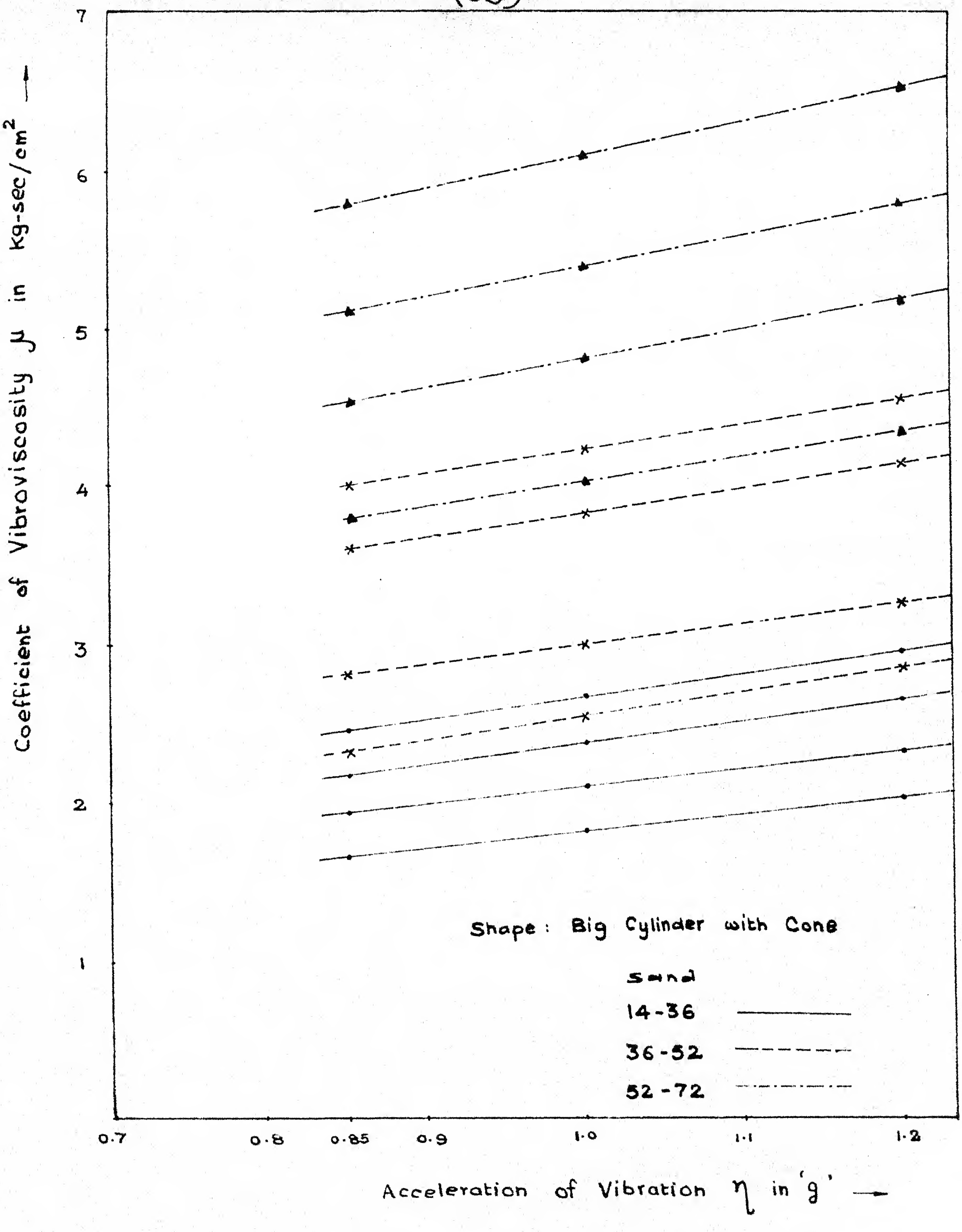


FIGURE 4.6 : EFFECT OF ACCELERATION OF VIBRATION ON VIBROVISCOSITY

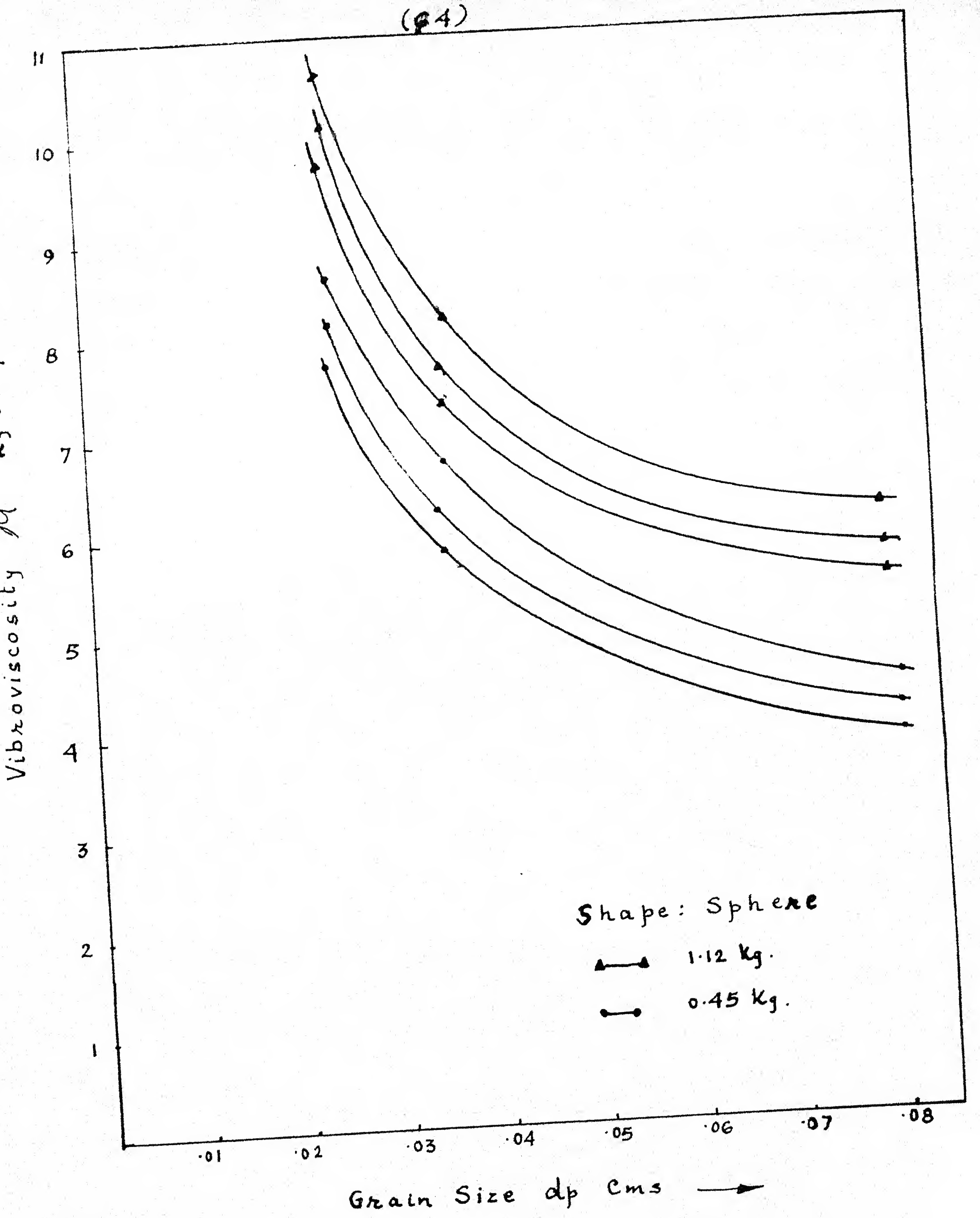


FIGURE 4.7A : EFFECT OF GRAIN SIZE ON VIBROVISCOSITY

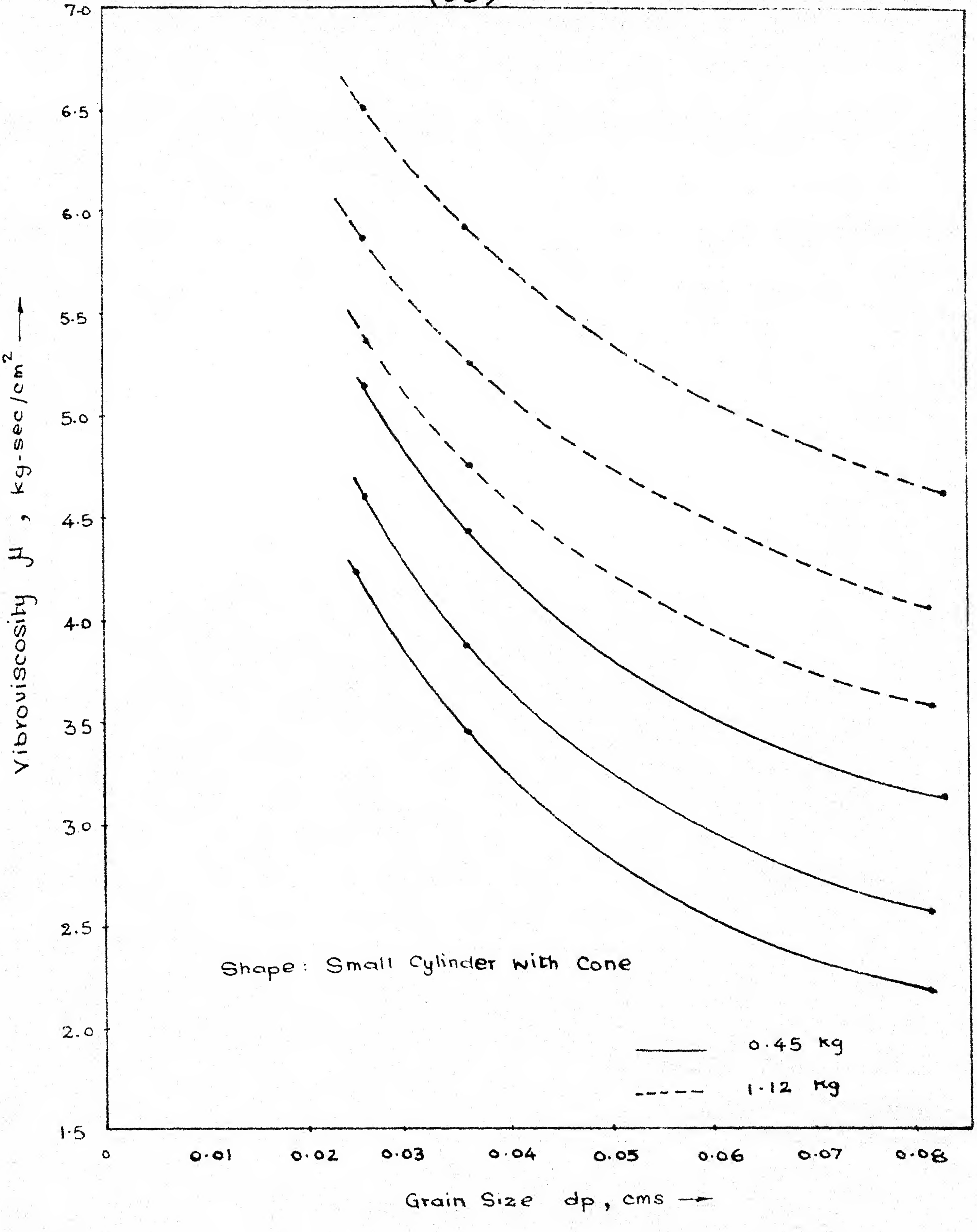


FIGURE 4.7 B : EFFECT OF GRAIN SIZE ON VIBROVISCOSITY

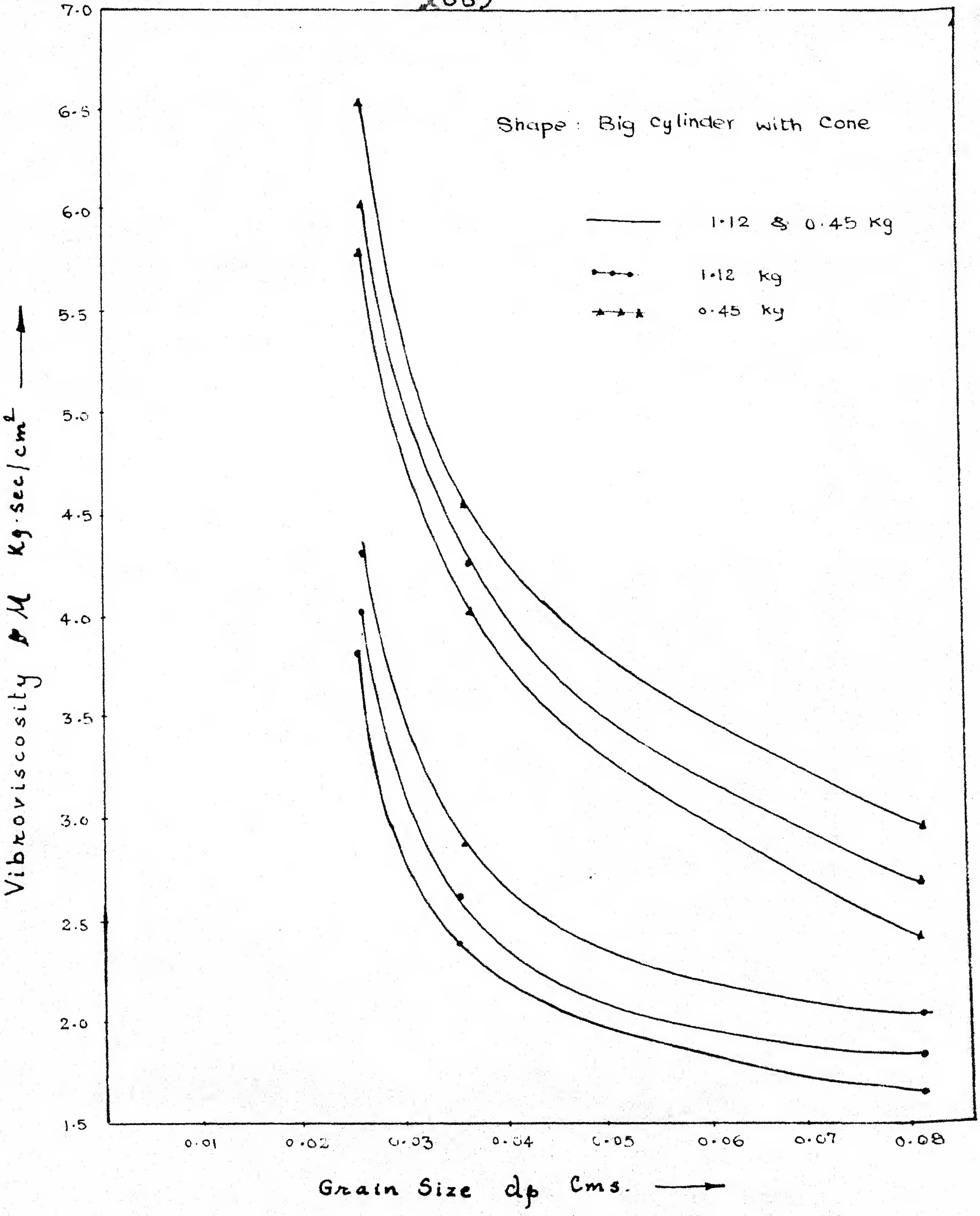


FIGURE 4·7C : EFFECT OF GRAIN SIZE ON VIBROVISCOSITY

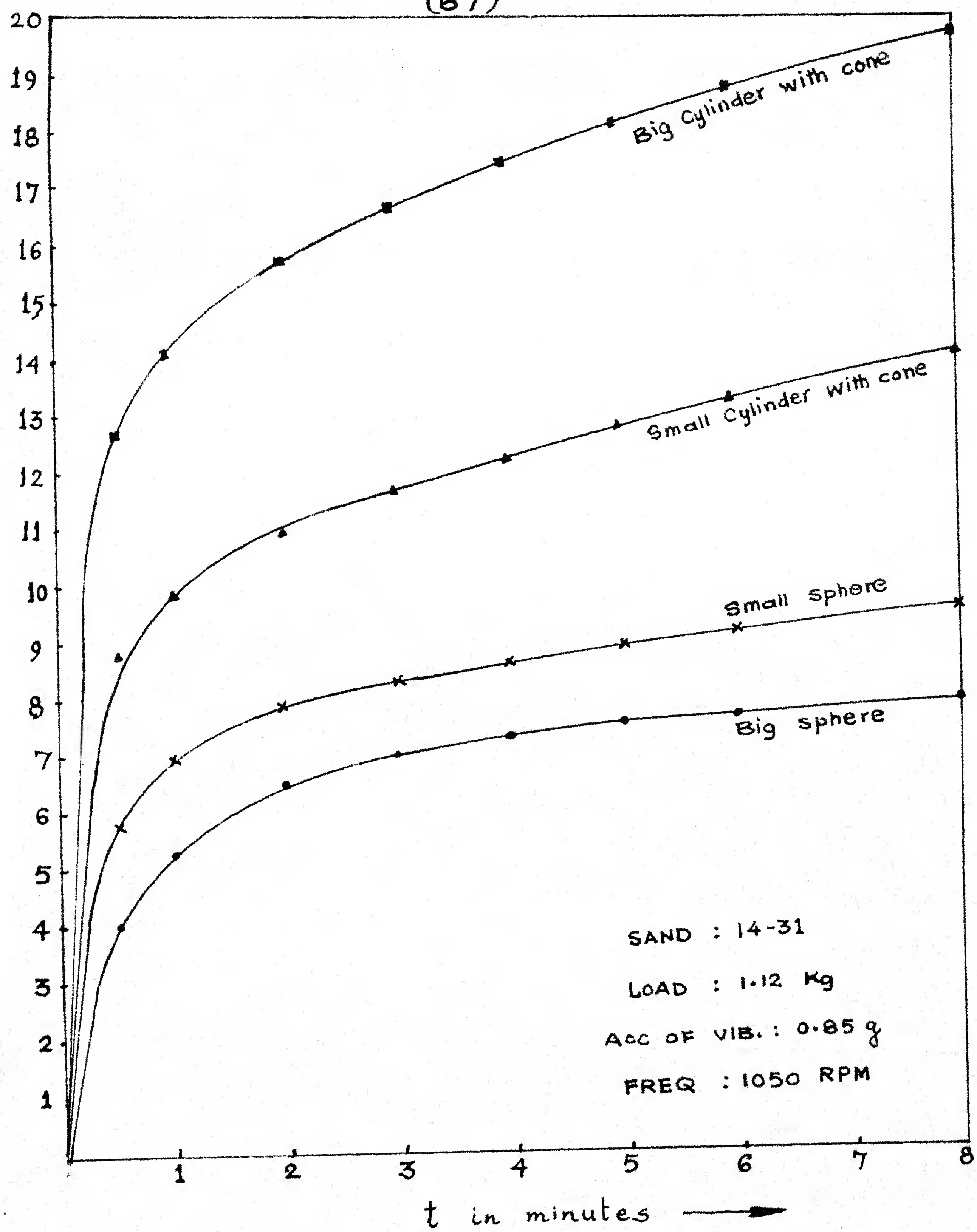


FIGURE 4.8 : SINKING BEHAVIOR OF DIFFERENT BODIES

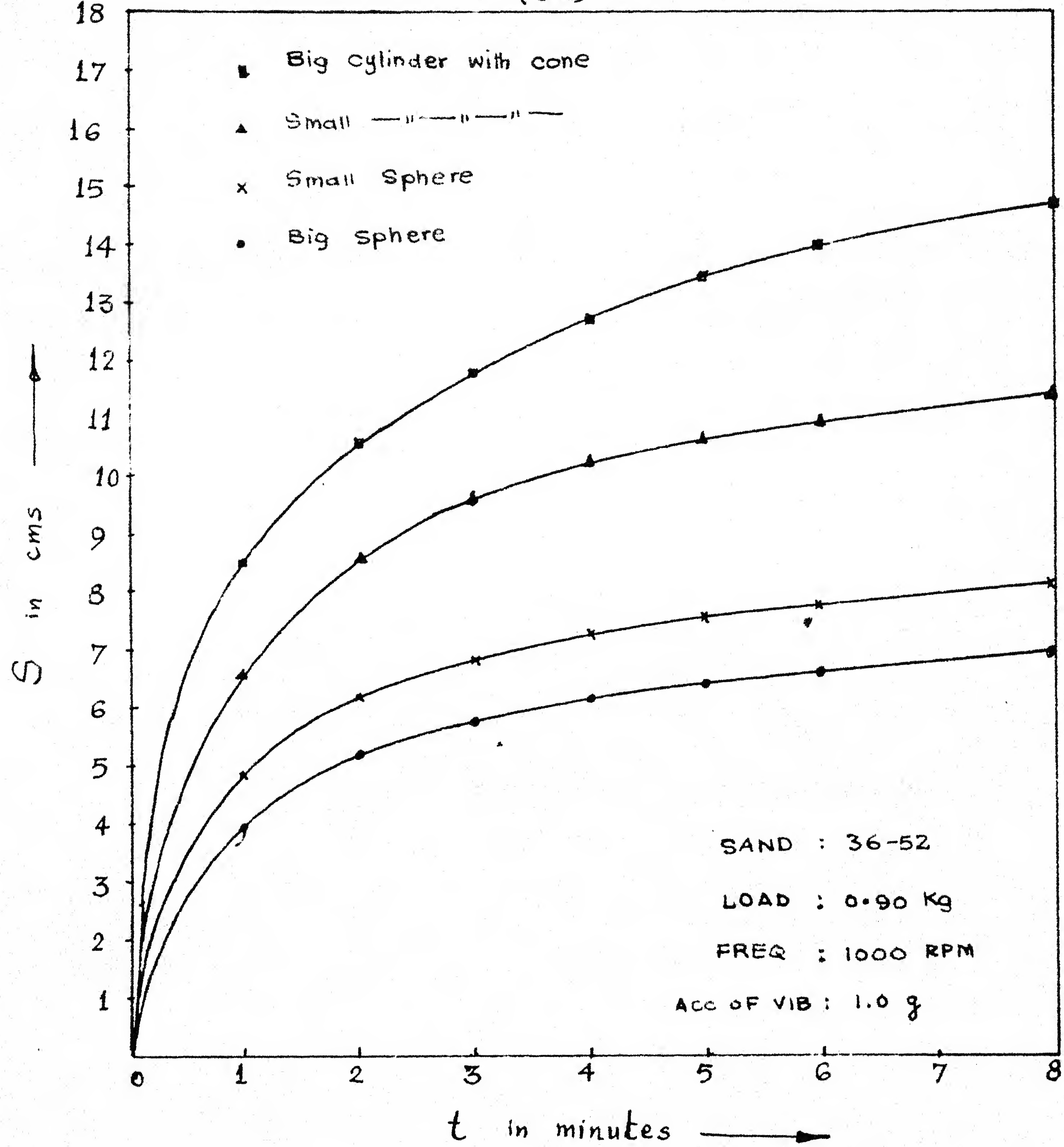


FIGURE 4.9 : SINKING BEHAVIOR OF DIFFERENT BODIES

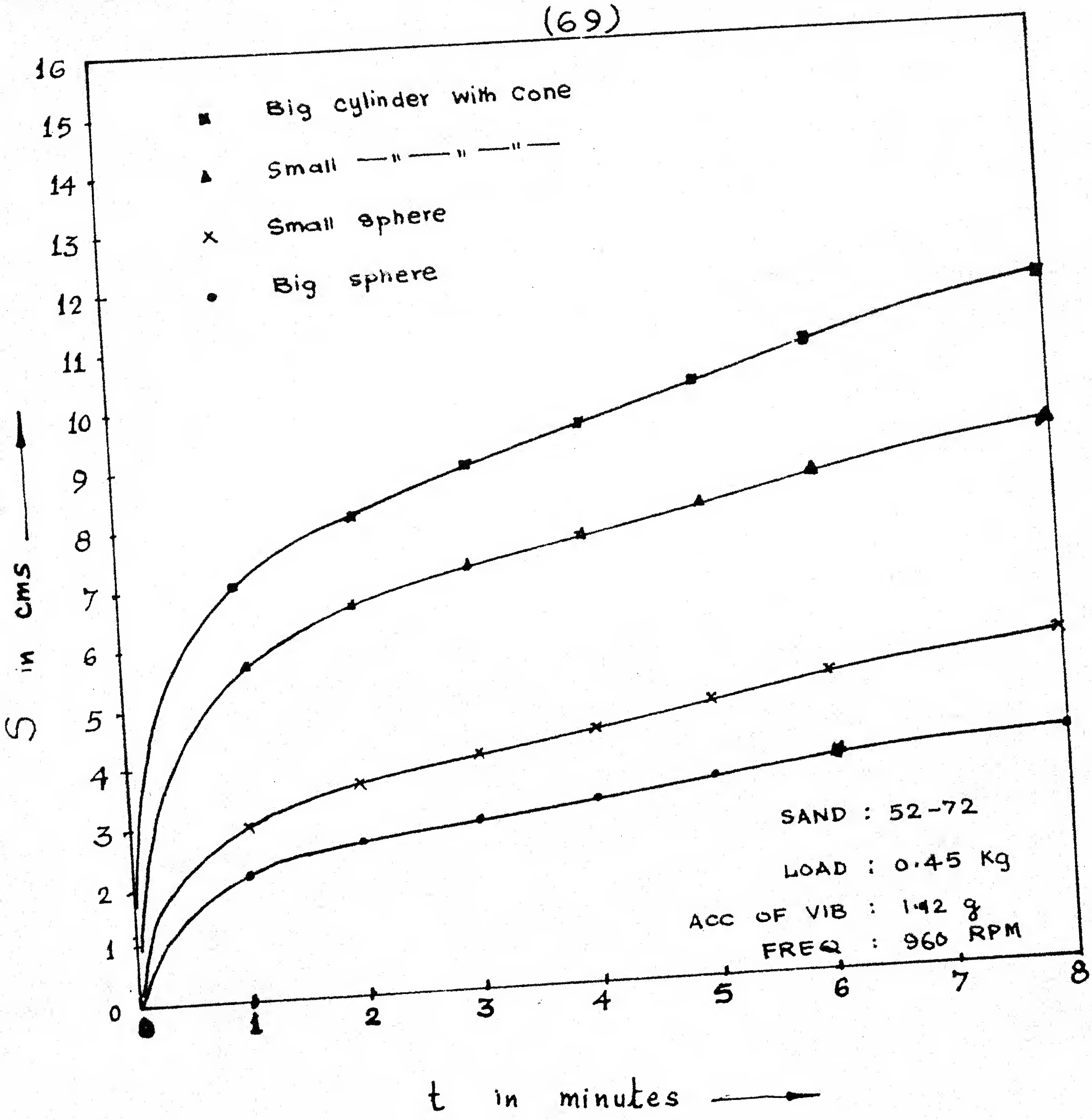


FIGURE 4.10 : SINKING BEHAVIOR OF DIFFERENT BODIES

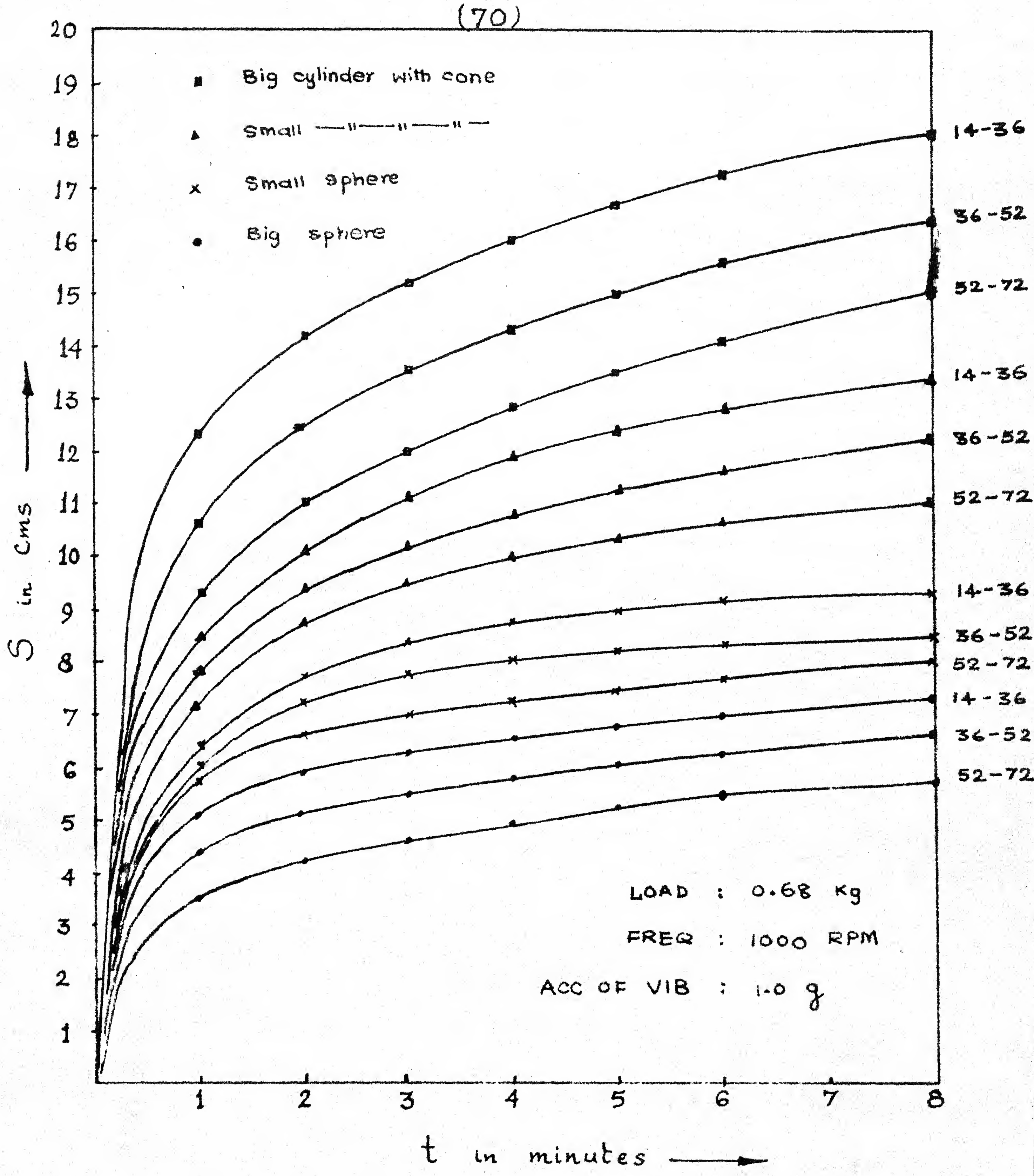


FIGURE 4.11 : EFFECT OF GRAIN SIZE ON SINKING OF BODIES

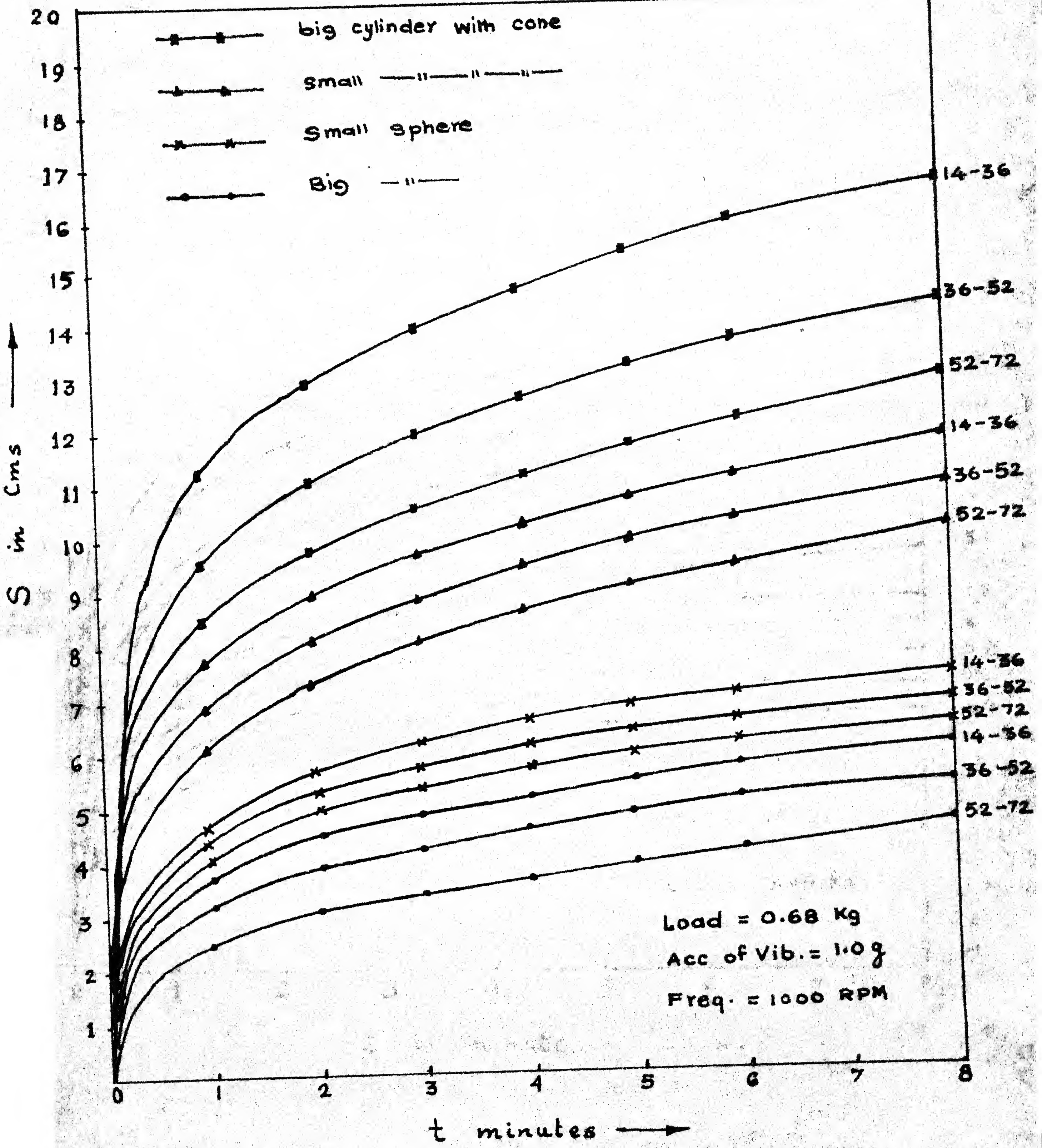


FIGURE 4.12 : EFFECT OF GRAIN SIZE ON SINKING OF BODIES

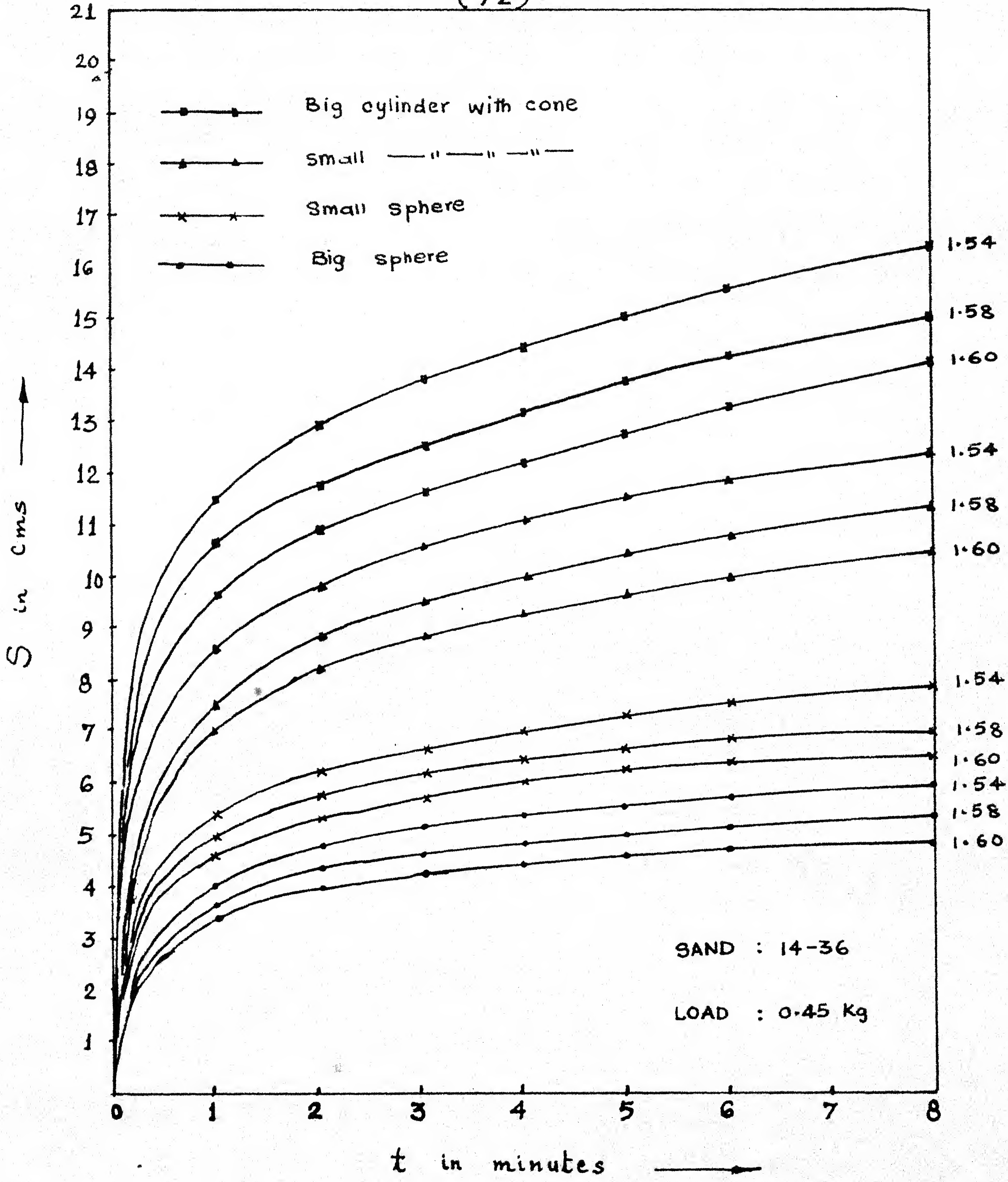


FIGURE 4·13 : EFFECT OF DENSITY ON SINKING OF BODIES

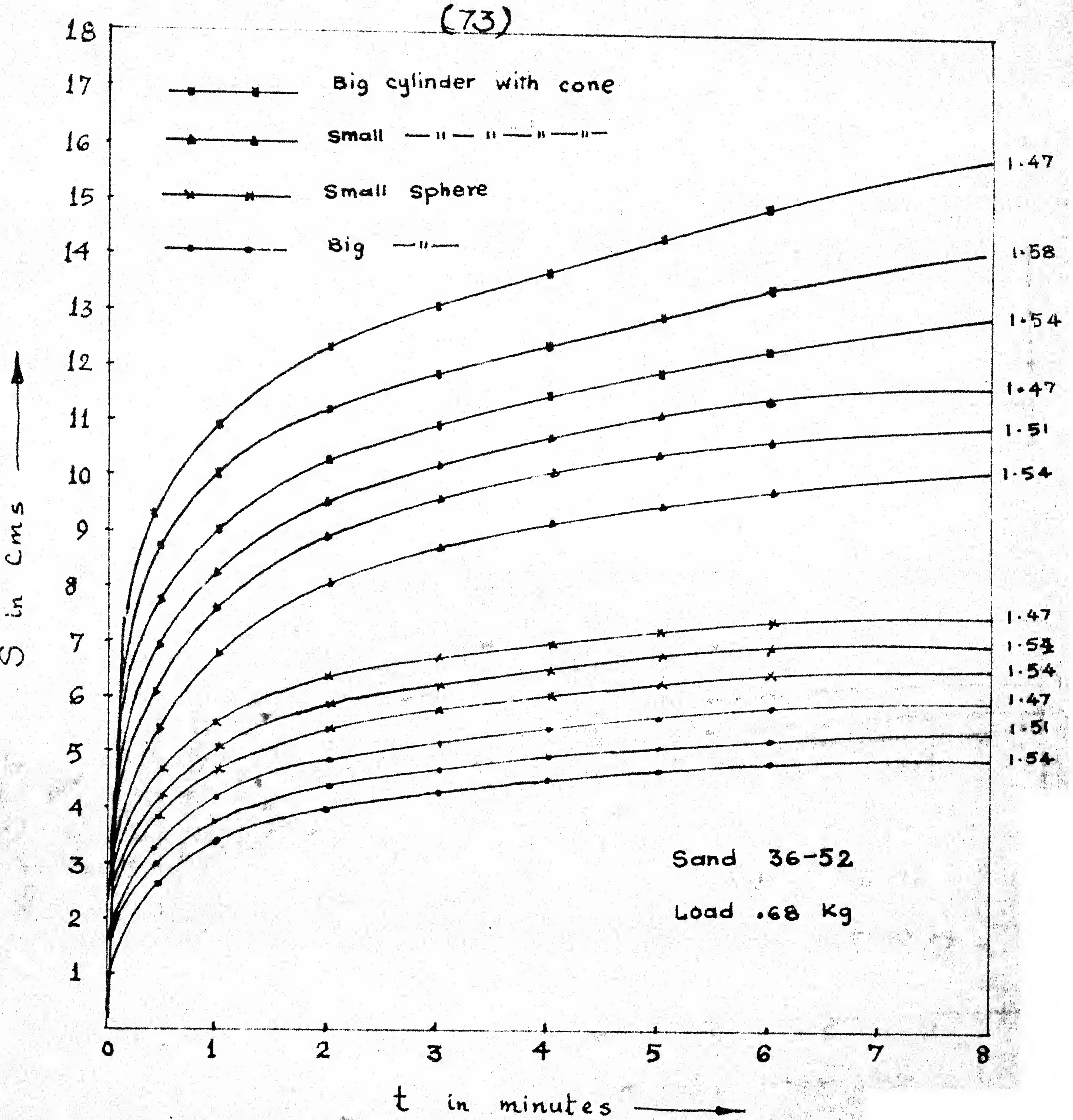


FIGURE 4.14 : EFFECT OF DENSITY ON SINKING OF BODIES

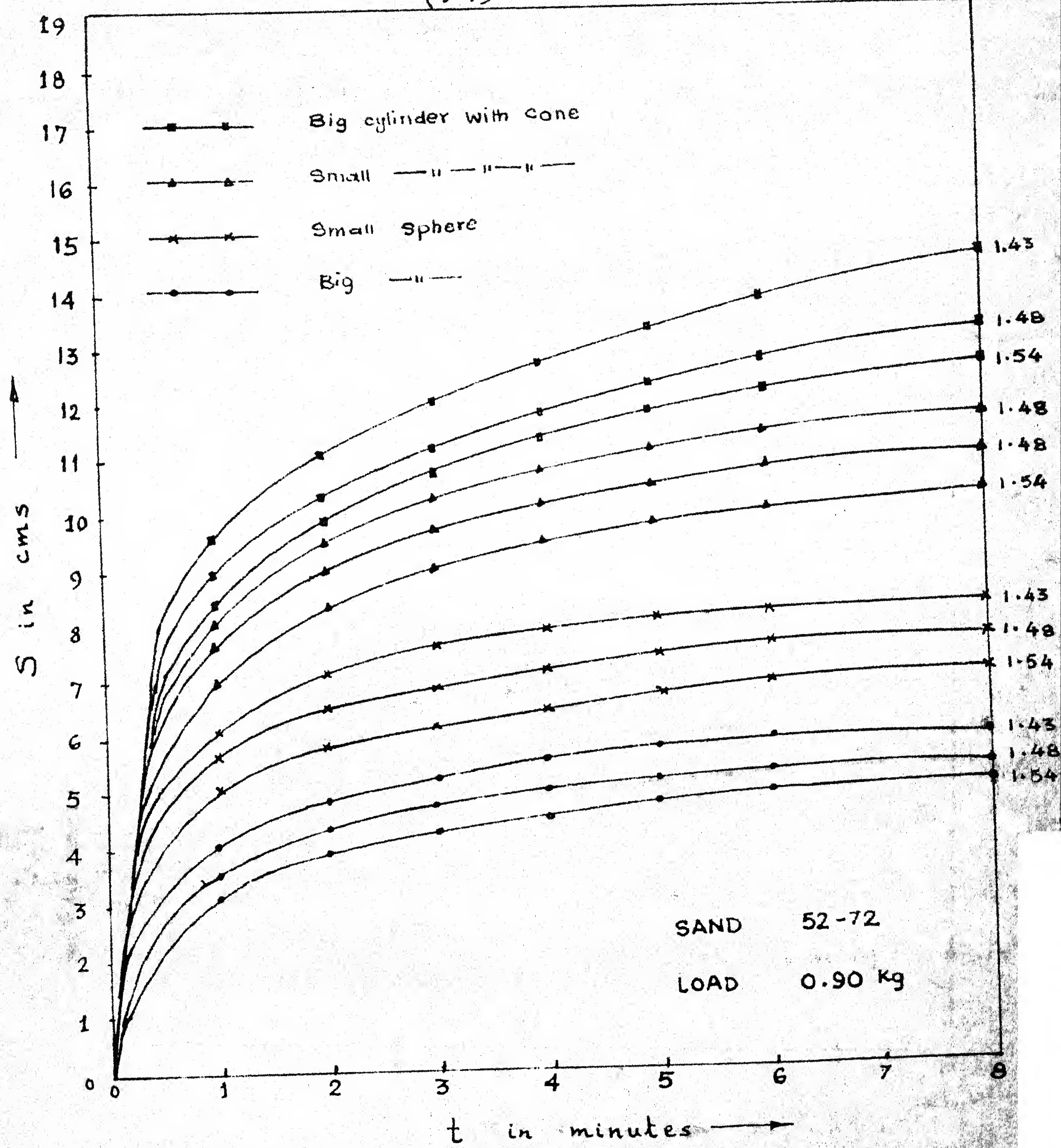


FIGURE 4.15 : EFFECT OF DENSITY ON SINKING BODIES

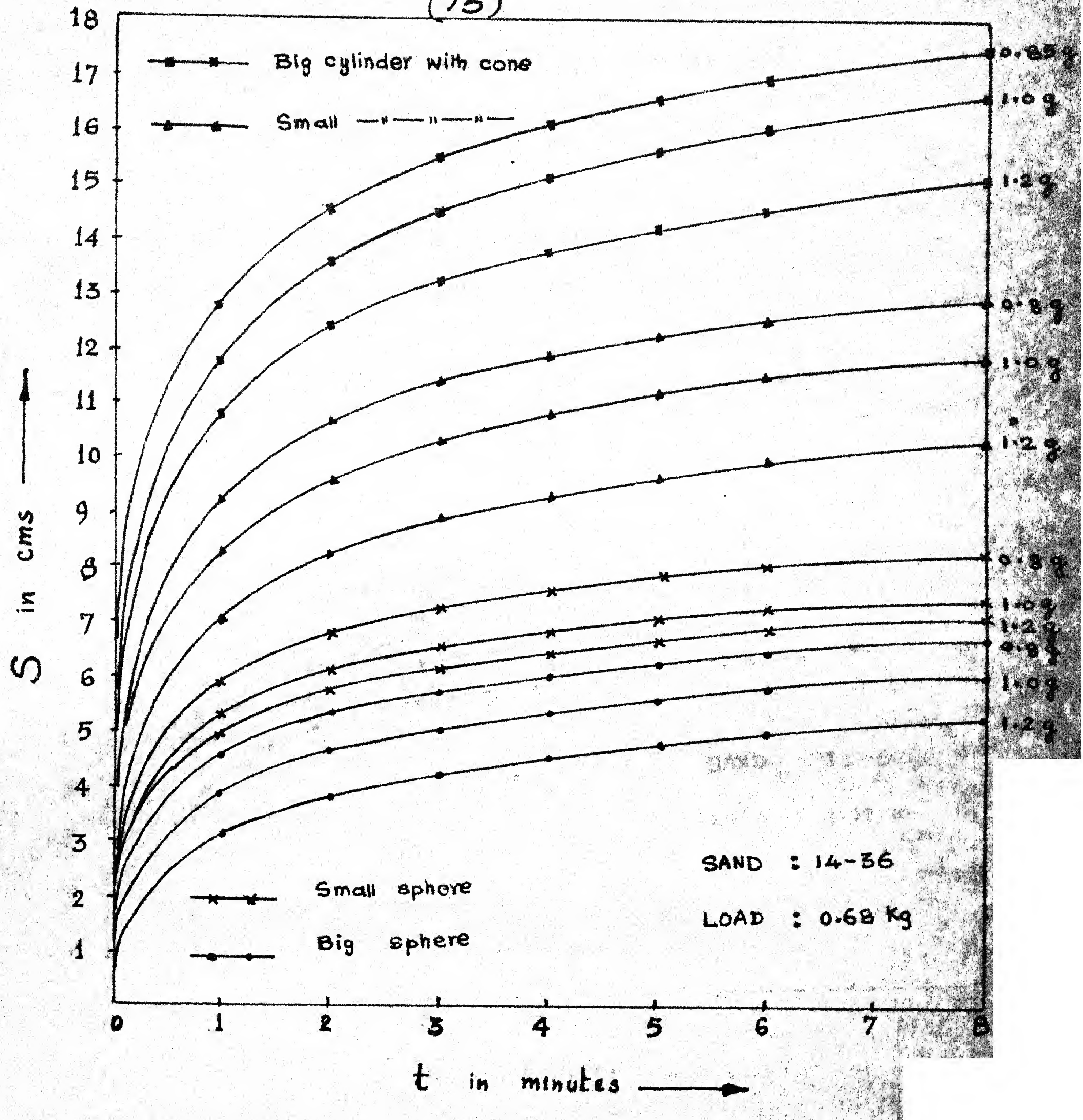


FIGURE 4.16 : EFFECT OF ACCELERATION OF VIBRATION ON SINKING OF BODIES

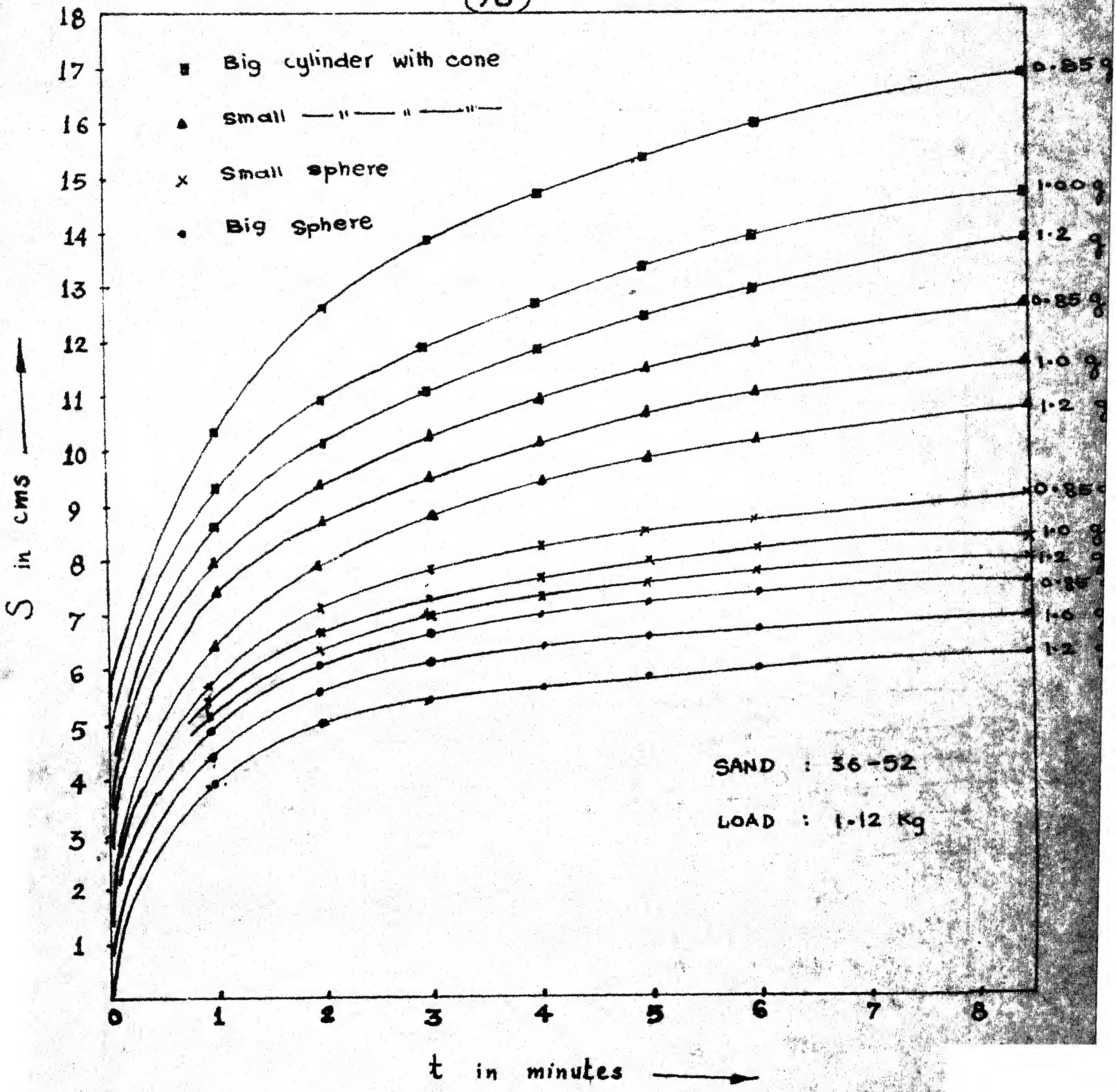


FIGURE 4.17 : EFFECT OF ACCELERATION OF VIBRATION ON SINKING OF BODIES

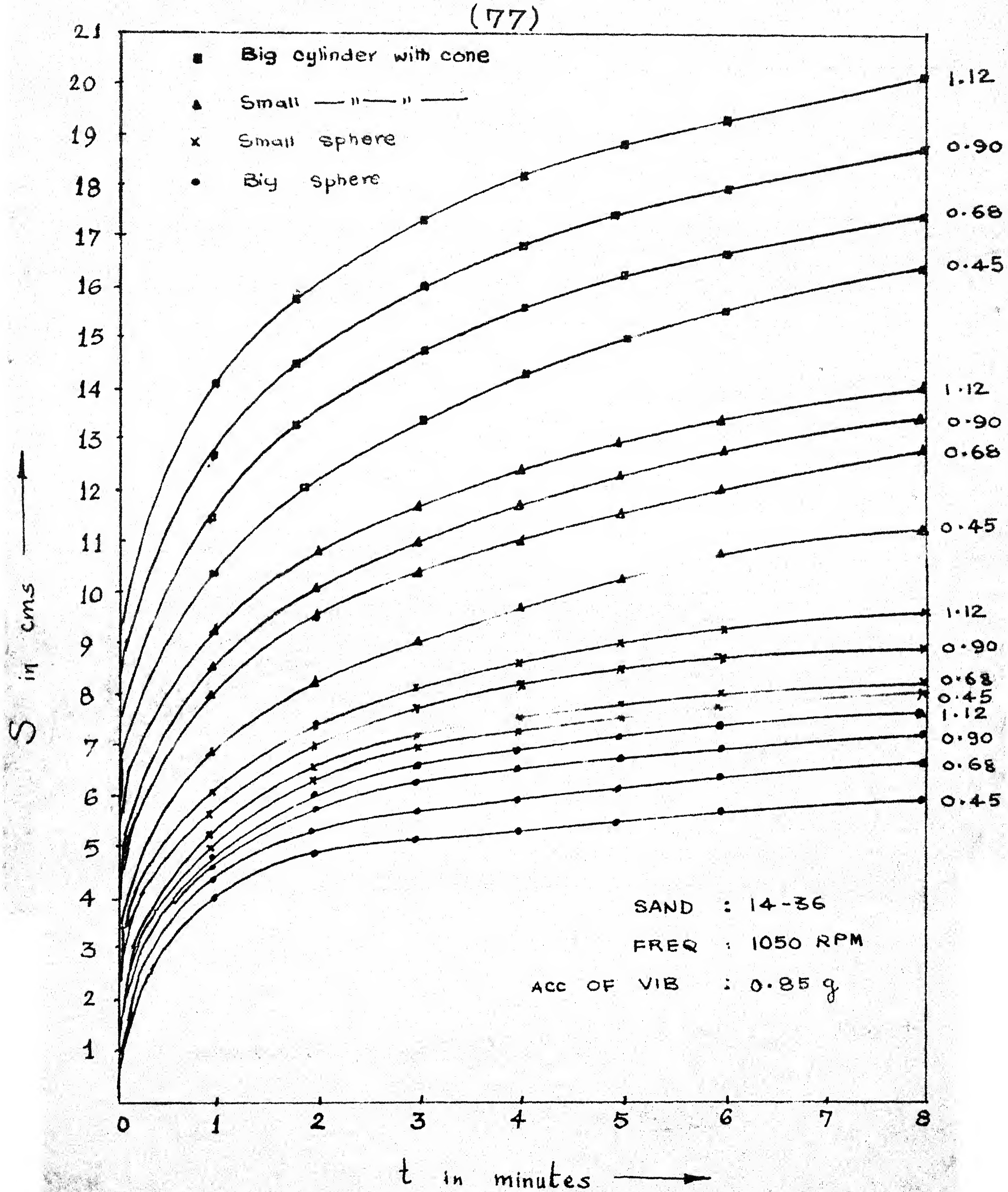


FIGURE 4.18 : EFFECT OF SURCHARGE LOAD ON SINKING OF BODIES

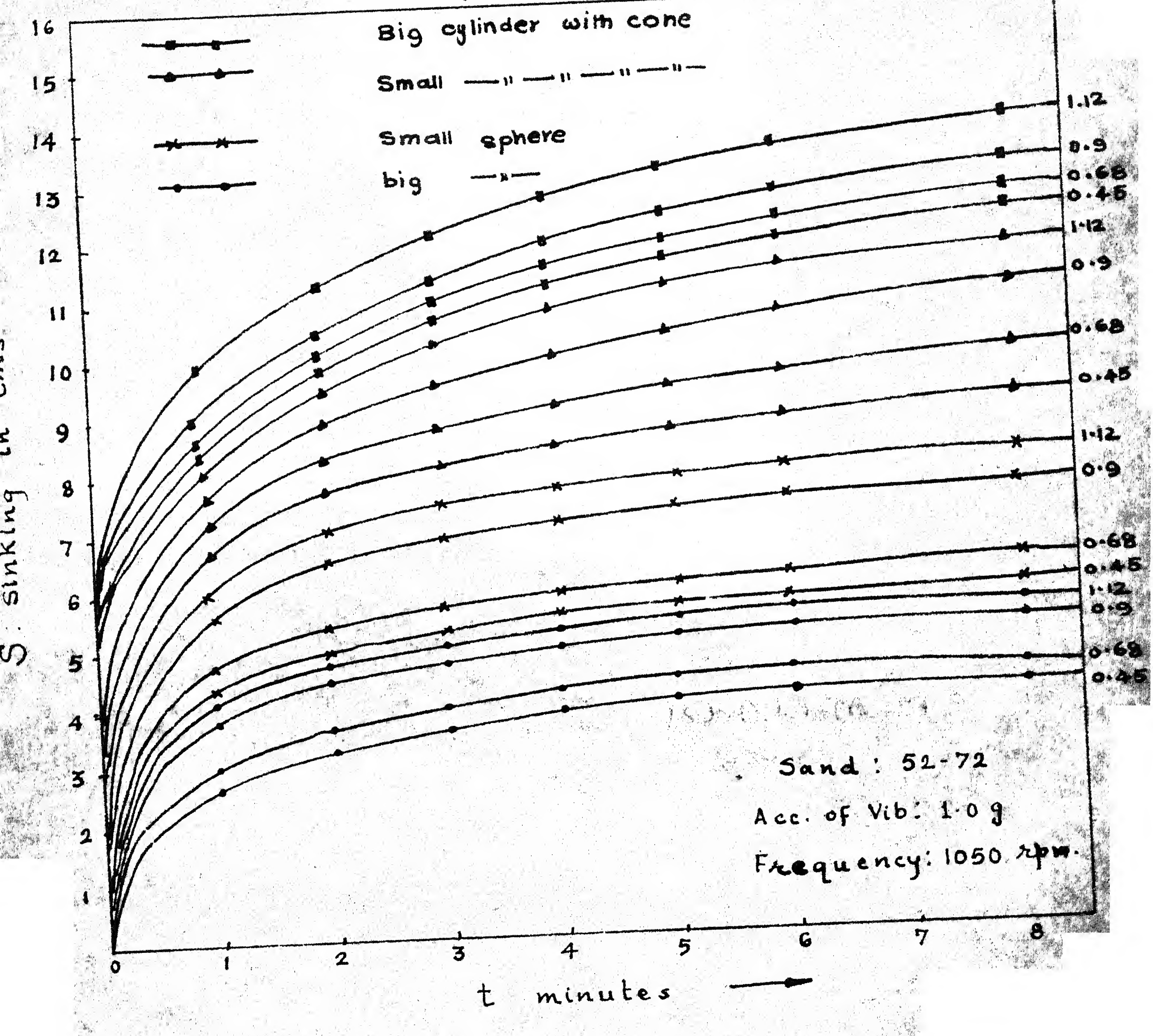


FIGURE 4.19 : EFFECT OF SURCHARGE WEIGHT ON SINKING OF BODIES